Appendix 10

Thyroid Cancer in Ukraine and Belarus after the Chernobyl Accident: Baseline and Total Incidence

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ABSTRACT

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. Average thyroid doses due to the Chernobyl accident were assessed for every birth year in the period 1968-85. Census data were used to derive the population in 1986. Case data were thyroid cancers operated in the period 1986-2001 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 1986-89, the baseline rate is increased by about a factor of 4 for females in the upper group for the whole period 1990-2001, and in the lower group for the period 1998-2001. The increase is less expressed in the other cases and for males in general. The baseline cases is 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.

Medical Subject Headings

Incidence, Mass screening, Radiation, Thyroid neoplasms

INTRODUCTION

In the areas contaminated with ^{131}I in April/May 1986 due to the Chernobyl accident, a drastic increase of the thyroid cancer incidence has been observed among those who were children or adolescents at the time of the accident (1, 2). Whereas in Ukraine the thyroid cancer incidence increases with an approximately constant rate since 1989 (3, 4), the initially steeper increase in Belarus slowed down in the second half of the nineties (5).

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 (6). The summary of published data on screening programs (7-13) in Table 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.

Several approaches have been made to estimate how much of the thyroid cancer incidence in the areas affected by the Chernobyl accident is directly due to the radiation exposure and how much is due to the baseline incidence under the conditions of an intensified surveillance of thyroid diseases:

- Likhtarev et al. (14) assumed that the total thyroid cancer incidence in the period 1986-89 can be used for the baseline incidence up to the year 1992, when the *Order of the* (Ukrainian) *Ministry of Public Health on the Improvement of Endocrinologic Help to the Population* was issued. According to this order the Chernobyl register for thyroid cancer was established. For the period after 1992, Likhtarev et al. (14) used the cancer incidence among those born after 1986, *i.e.*, those who were not exposed to the accidentally released iodine. For age 0-10, the estimated incidence in the second period was by a factor of 1.27 larger than in the first period. The estimate is based on a small number of 11 cases, also it is not clear whether the incidence among children born after 1986 can be applied to those who were exposed by the Chernobyl accident.

- Jacob et al. (15) argued that a large fraction (45%) of the operated tumors were in a late stage and would have become clinically relevant independent of any screening. They concluded that in the highly affected area the baseline incidence is about a factor of 3 larger than what was reported for Belarus for the period 1983-87 (16). Shortcomings of this approach are that no temporal or regional tendencies have been explored although these might well be quite high.

It is the purpose of this paper to present thyroid dose estimates and cancer data for the birth-year cohort 1968-85 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 six oblasts of Belarus and for two cities and the 25 oblasts of Ukraine (Fig. 1).

Thyroid dose estimates

Ukraine. Thyroid doses of the Ukrainian population have been reconstructed by Likhtarov et al. (Radiation Protection Institute, Kyiv, unpublished manuscript). In brief, count rates measured in May/first half of June 1986 in front of the neck of 130,000 children and adolescents were corrected for background and for contributions of radiocesium contained in the human body. The ^{131}I content in the thyroid at the time of the measurement was obtained by corresponding calibration factors. The time integral of the ^{131}I activity was estimated with the help of intake functions that were derived from in total 14 000 questionnaire responses, which were obtained in 1992 to 1994.

Time integrated activities $\widetilde{A}_{ref,s,j}$ 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 the measured persons. Thyroid doses in the 36 age-sex groups in each of the 748 settlements with a sufficient number of ^{131}I measurements were obtained according to

$$\overline{D}_{a,s,j} = \widetilde{A}_{ref,s,j} \cdot f_{a,s} \cdot \alpha_I / M_a , \tag{1}$$

where α_I is the energy absorbed in the thyroid per decay of ^{131}I, and M_a the thyroid mass.

A radioecological model was developed to estimate average integrated ^{131}I activities $\widetilde{A}^{ecol}_{ref,s,j}$ for 12-14 year olds. The ratios $\widetilde{A}^{ecol}_{ref,s,j} / \widetilde{A}_{ref,s,j}$ for the settlements, in which ^{131}I measurements had been performed, have been averaged in order to obtain scaling factors $K_{rayon,s}$ for rayons (districts) with measurements. In these rayons, average thyroid doses in settlements $j*$ without ^{131}I measurements were obtained according to

$$\overline{D}_{a,s,j*} = (\widetilde{A}^{ecol}_{ref,s,j*} / K_{rayon,s}) \cdot f_{a,s} \cdot \alpha_I / M_a . \tag{2}$$

The values of $K_{rayon,s}$ were in the range of 0.9 (for girls in Chernihiv town) to 8.4 (for boys in Luhyny Rayon in Zhytomyr Oblast) and decreased with decreasing ^{137}Cs activity. An analytical approximation of this dependence was extended to oblasts (regions) and rayons in which no measurements of the ^{131}I activity had been performed in order to obtain scaling factors $K_{oblast,s}$. For settlements $j**$ in oblasts without ^{131}I measurements, estimates of thyroid doses in the 36 age-sex groups were obtained according to

$$\overline{D}_{a,s,j**} = (\widetilde{A}^{ecol}_{ref,s,j**} / K_{oblast,s}) \cdot f_{a,s} \cdot \alpha_I / M_a . \tag{3}$$

Dose estimates for the oblasts were obtained by averaging the settlement doses with weights according to their population.

For the example of Kyiv City, 18 year olds had in average 20 mGy thyroid dose, 1 year olds about 100 mGy (Fig. 2). In the age group 11-17, the average dose of girls is smaller than the average dose of boys.

Belarus. Thyroid doses for the Belarusian population have been derived by Shinkarev et al. (Institute of Biophysics, Moscow, unpublished manuscript). In brief, dose estimates for 125,000 persons who had the ^{131}I activity in the thyroid measured during May/early June 1986 were derived. The relative importance of the inhalation and the ingestion pathway was determined questionnaire responses including information on the consumption of locally produced milk.

Dose estimates for Minsk and Gomel City in each age group are averages of the individual dose estimates of those who lived in their cities in April-May 1986. The estimation of average doses to children in other settlements with more than 10 measurements of the ^{131}I activity in the human thyroid was based on averages of measured doses and took into account generic age dependencies of thyroid doses for different radioecological conditions.
The average age-dependent thyroid doses for children in the remaining settlements of the six Belarusian oblasts were calculated using a modification (17) of the semi-empirical model (18). The model is based on the relationship between the mean thyroid dose of adults that were derived from exposure rate measurements in front of the human neck and the deposition density of ^{131}I and ^{137}Cs. In settlements with dominantly dry (wet) deposition the derived factor is 1.2×10^{-7} Gy Bq^{-1} m^{2} (1.3×10^{-8} Gy Bq^{-1} m^{2}). Intermediate values were used for settlements in which both deposition modes had been important. Reduction factors were applied to doses for settlements with special conditions, *e.g.*, where cows were put on pasture after the radioactive fallout had occurred, where residents were evacuated or relocated, where milk consumption was ceased, or where iodine prophylaxis was applied.

The data on ^{137}Cs ground-deposition density in Belarusian settlements were taken from ref. (19). For a small part of the Belarusian settlements, the ratio of the ^{131}I- to the ^{137}Cs-deposition could be derived from spectrometric measurements conducted in May through July 1986. For the overwhelming majority of the settlements, the general pattern of the ratio of the ^{131}I to the ^{137}Cs in the deposition in Belarus was used.

Doses to children were derived from doses to adults by applying generic factors for the age dependence. The ratio of doses calculated for people born in 1985 and in 1968 is 6.6 in the six oblasts (Fig. 2), 4.4 in Gomel City and 8.0 in Minsk City. No information was given on differences between doses to girls and to boys.

For the present analysis, the sex ratio of the doses in Kyiv City was used to derive sex-specific doses $D_{s,i}^{city}$ for the birth cohort *i* in Minsk and Gomel City according to

$$D_{s,i}^{city} = D_{av,i}^{city} \cdot D_{s,i}^{K} / D_{av,i}^{K}, \qquad (4)$$

with

$$D_{av,i}^{K} = (PY_{f,i}^{K} D_{f,i}^{K} + PY_{m,i}^{K} D_{m,i}^{K}) / (PY_{f,i}^{K} + PY_{m,i}^{K}), \qquad (5)$$

where the index *s* can be *f* for females and *m* for males, and the index *K* stands for Kyiv. In the same way, sex-specific doses for the oblasts of Belarus were derived using the sex-ratio of the doses in Chernihiv Oblast.

There is a second, a radioecological approach to estimate age dependent average doses of the Belarusian settlements (20). In order to estimate the dependence of the results on dosimetry, alternative calculations were performed with this radioecological approach.

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 or because of death are considered to be small, because the population group considered is young.

Ukraine. 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 (21, 22). A linear interpolation was applied to derive the population structure in 1986.

Belarus. The demographic situation in 1986 was estimated from the age-gender structure in the Belarusian oblasts as determined in the 1989 census (5). Age-gender specific death rates for the period 1986-88 were used to estimate the population structure in 1986. Statistical reports of the Ministry of Health of the Belarusian SSR for 1986 were used to verify the results.

Thyroid cancer cases

The data files used contain for all thyroid cancer cases the place of residence at the time of the accident. For some of the cases, not the full birth data, but only the birth year was available. Therefore, throughout the paper only birth years were used, and age-at-surgery is defined by the difference of the year of surgery and the birth year.

Ukraine. The clinical-morphologic register at the Institute of Endocrinology and Metabolism of the Academy of Medical Sciences of Ukraine has been described elsewhere (23, 3, 4). According to the *Order of the Ministry of Public Health on the Improvement of Endocrinologic Help to the Population* from 1992, all thyroid cancer cases among subjects who were aged up to 18 years at the time of the Chernobyl accident and who were operated in Ukraine have to be reported to the register.

The present study uses data of the register for the birth cohort 1968-85 and for the operation year period 1986-2001 (Table 2). The largest number of cases have been reported for Kyiv City (305 cases) with a ratio of cases among females and males (F/M ratio) of 3.4. The highest F/M ratios have been reported for regions, which are far from the Chernobyl reactor plant and which were not in the main wind directions during the release, for example 8.3 for Odesa Oblast.

Belarus. A data exchange of three registers was performed in order to achieve consistent data sets. These were

- the Belarusian State Chernobyl Register, which was established in 1993 according to a decree of the Council of Ministers of Belarus, containing data about liquidators and citizens of areas with ^{137}Cs contaminations exceeding 555 kBq m^{-2}.
- the Belarusian Cancer Register, which was established in 1953 according to a directive of the Ministry of Public Health of the USSR. The register does not contain information about the place of residence at the time of the Chernobyl accident.
- the medical history records of patients treated in the National Scientific and Practical Center of Thyroid Tumors in Minsk, in which all thyroid cancers of Belarusian children have to be performed.

The largest number of cases has been reported for Gomel Oblast (549 cases) with an F/M ratio of 1.5 (Table 2). The highest F/M ratio again has been reported for the oblast with the largest distance to the Chernobyl reactor plant (Vitebsk Oblast with a ratio 5.2).

Analysis of data

Grouping of oblasts/cities according to baseline thyroid cancer incidence. The total thyroid cancer incidence rate I_j for the birth cohort 1968-85 in oblast/city j was plotted against the average thyroid dose D_j (Fig. 3). The diagram was subdivided by two lines in three areas of high, middle and low baseline thyroid cancer incidence. The lines corresponded to an incidence rate for an excess relative risk per dose, β, of 20 Gy^{-1}

$$I_k = a_k \cdot (1+ \beta \cdot D), \qquad k = 1,2 \tag{6}$$

and to baseline incidence rates a_k, which were chosen in such a way that there was in the three regions above, between and below the two functions about an equal number of oblasts/cities. As shown in Table 3, the value of β is intermediate to what has been found in earlier analyses (5, 14, 15, 24).

In order to study the influence of the classification on the final results, all calculations were repeated for a classification of the oblasts according to incidence rates for an excess absolute risk per dose, α, of 2 cases per 10^4 personyear-Gy,

$$I_k = a_k + \alpha \cdot D, \qquad k = 1,2. \tag{7}$$

Baseline incidence rate. Separate analyses were performed for the three groups l of high, middle and low thyroid cancer incidence, and for the two sexes, s. Further, the data were subdivided in five-year intervals m of age at operation (1-4, 5-9, 10-14, ..., 30-33) and four-year intervals n of operation years (1986-89, …, 1998-2001). In each of these subgroups, a Poisson regression of the incidence rate I_{jsmn} in oblast/city j was performed as a function of the average dose D_{jsmn} according to a linear risk model

$$I = \exp(a_{lsmn}) + b_{lsmn} \cdot D, \tag{8}$$

where a_{lsmn} and b_{lsmn} are two fit parameters derived from data points for 11 or 12 oblasts/cities each. The value $I_{lsmn} = \exp(a_{lsmn})$ is an estimate of the radiation-independent (baseline) incidence rate in the sub-group $lsmn$. The regressions were performed with the program Epicure (Hirosoft International Corporation, Seattle, WA).

The age dependence of the incidence rates was obtained by weighing I_{lsmn} with the inverse of their variance and fitting to the functions

$$I = c_{lsn} + d_{lsn}\, age^{e_s}, \tag{9}$$

where c_{lsn}, d_{lsn} and e_s are fit parameters, and *age* is the difference between year of operation and year of birth. The fit parameters were bound to be positive. The fits were performed with the program Origin 5.0 (Microcal Software, Northampton, MA).

RESULTS

Grouping of oblasts/cities according to baseline incidence

The thyroid cancer incidence rate in the period 1986-2001 for the birth cohort 1968-85 is in 31 of the 35 oblasts/cities in the range of 4 to 50 cases per 10^6 personyears (Fig. 3). The minimum value is about 1 case per 10^6 personyears (Ternopil Oblast), the maximum value about 100 cases per 10^6 personyears (Gomel Oblast).

According to the data, average doses of 32 of the oblasts/cities are estimated to be in the range of 0.006 to 0.1 Gy. The minimum value is about 0.004 Gy for Vitebsk Oblast, the maximum value is 0.44 Gy for Gomel Oblast.

Using the grouping according to eq. (6), the majority of Belarusian oblasts/cities and the majority of oblasts/cities in which measurements of the ^{131}I content in the human thyroid were performed in May/June 1986 belong to the upper group of baseline thyroid cancer incidence (Table 4). Exceptions are Minsk City and Zhytomyr Oblast (both middle group).

Different methods of grouping of the oblasts/cities and/or different dose estimates have only a small influence and the grouping of the oblasts/cities (Table 5).

Age- and time dependencies of the baseline incidence

Main results. As shown in Table 6, in total 96 groups (3 groups of oblasts/cities, 2 sexes, 4 age groups, 4 calendar-year periods) were considered for the estimation of baseline incidence rates I_{lsmn} according to eq. (8). In 87 cases results could be used for further analyses (Fig. 4), in the other nine cases the fits did not converge or fit parameters had very large uncertainties. The estimated baseline incidence is higher for females than for males, increases from the lower to the upper group of oblasts/cities, and increases with increasing age and calendar year.

The fit of eq. (9) gives a smooth approximation of the point estimates for the baseline incidence (Fig. 4). The exponent of the age was found for females to be 2.8 and for males 2.1 (Table 7). For 20-year old females, the baseline is estimated to be about a factor of 5 larger than for males. The incidence rate in the upper group is for females (males) by about a factor of 3.5 (6) larger than for the lower group.

Compared to 1986-89, the baseline rate is increased by about a factor of 4 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 for the period 1990-93. All other cases exhibit an increase of about a factor 2.

Results for the grouping according to eq. (7) or dose estimates with the radioecological model. For the upper group, the central age decade of the curves presented in Fig. 4 agrees with the results according to eq. (7) in general within 5 percent. Applying the radioecological model, a similar good agreement is obtained for females. For males, the results agree in general within 25 percent, with the exception of the calendar year period 1986-89 where larger differences are observed.

For the middle group, the results of the different methods agree in general within 20 percent. However for the period 1994-97, the results for the grouping according to eq. (7) are about a factor of 2 larger than the main results in Fig. 4. For the lower group, the agreement is less good.

Concerning the comparison of the baseline incidence rate in 1986-89 to later periods, in general the results do not depend on the method. However, for the grouping according to eq. (7) no increase is observed in the lower group, and for the doses according to the radioecological model an increase by a factor of 3 is observed for females in the upper group for the period 1994-2001.

Total and baseline annual number of thyroid cancer cases

In Ukraine, the annual number of cases is increasing with a constant slope since 1989 until the end of follow-up (Fig. 5). In Belarus, a strong increase in the period 1990-94 was followed by a more modest increase. There seemed to be a constant level of the incidence in Belarus in the period 1996-2001, however, the case number reported for 2002 (not analyzed in this paper) indicates a continuation of the modest increase since 1995. The time dependence of the thyroid cancer incidence in the more contaminated regions (Zhytomyr, Chernihiv and Kyiv in Ukraine, and Gomel in Belarus) are similar to the dependence in the whole countries.

According to the estimates of the present analysis, baseline cases contribute about 65 percent in Ukraine and 45 percent in the three northern oblasts, in Belarus they contribute 30 percent. In all cases, the baseline contributes for females significantly more to the total incidence than for males.

The results of the different methods agree within 10 percent.

DISCUSSION

The results indicate that the case detection and reporting is more effective in Belarus and in the areas with measurements of the ^{131}I activity in the human thyroid than in other parts of Ukraine. This is supported by the fact that the frequency of small tumors (≤ 1 cm) in Belarus is about 35 percent (25) and exceeds considerably the frequency in Ukraine, which was reported to increase from 3.4 percent in 1986-1995 to 7.9 percent in 1996-2000 (3).

Other analyses of register data

Older register data. The thyroid cancer incidence in the period 1983-87 in Belarus, as it was reported in *Cancer in Five Continents* (16), was about 1 case per 10^6 PY for 10-year olds, and about 3 cases per 10^6 PY for 15-year olds. Compared to other countries, the incidence in Belarus was at the lower end. The data in the present study on the baseline incidence (Fig. 4, main part of Belarus belongs to upper group) for the period 1986-89 are higher by about a factor of 1.5, demonstrating the improvement of the case reporting.

Ecologic studies after the Chernobyl accident. Jacob et al. (15) estimated that the baseline incidence in the period 1991-95 in the Belarusian area highly contaminated by the Chernobyl accident was by factor of 3 (95% confidence interval: 1-5) larger than the data for 1983-87 in (16). According to the present analysis for the upper group, the factor is 3 (for 15-years olds) to 4 (for 20-years olds), confirming the assumptions of this earlier work. In two other papers (5, 14), lower baseline risks were assumed explaining why those studies obtained high estimates of relative risk.

The method applied in the present paper does not take into account possible correlations between the thyroid dose and an improved case detection and reporting, which is a possible bias for underestimating the baseline incidence. However, the comparison with the previous analyses (see above) does not give an indication for such an underestimation. It may be concluded that different efficiencies of case detection and reporting have contributed to the subdivision of the oblasts/cities in the upper, middle and low group of baseline incidence, and that within these groups there is no expressed correlation between dose and the screening within each of the three groups. This is also supported by the general agreement of the estimated baseline incidence of the total number of observed cases for the period 1986-89 (Fig.5), in which only a minor number of radiation induced cases is expected because of the latency time between exposure and cancer surgery. An exception is here Gomel, which seems to have a more effective case detection and reporting than the average of the upper group of oblasts/cities.

Cohort studies on thyroid cancer

Autopsy studies (26, 27) have revealed a high frequency of occult thyroid cancers, some of which may be detected by intensive screening methods in cohort studies. This may be one of the main reasons that the recall and screening program for people who had been treated at the Michael Reese Hospital (MRH) in Chicago by irradiation for benign head and neck diseases resulted in an increase of the thyroid cancer incidence by a factor of 7.4 (6). It is interesting to note that the increase among patients who received radiation exposures of less than 0.5 Gy was considerably larger.

The first screening campaign of the Ukrainian-American cohort study resulted in a thyroid cancer prevalence of 3200 cases per 10^6 persons (Table 1). The results of the second screening campaign (13) in the cohort correspond to an incidence rate in the range of 600-900 cases per 10^6 PY (1800 cases per 10^6 persons within two or three years since the first screening campaign). This is by a factor of 6-9 higher than the incidence rate in the most contaminated oblast (Gomel Oblast, see Fig.3), which can not be explained by a difference in exposure.

In summary, intensive screening in cohort studies of thyroid cancer lead to an incidence rate in the cohort that considerably exceeds the incidence rate in the population. It may be anticipated that the excess absolute risk per dose in the cohort will also exceed the corresponding risk in the population.

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Figure legends

Fig. 1. Study area in Belarus and Ukraine: 31 oblasts (regions) and four cities.

Fig. 2. Average thyroid dose due to ^{131}I incorporation after the Chernobyl accident in four oblasts/cities of Ukraine and Belarus.

Fig. 3. 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.

Fig. 4. Best estimates and geometric standard deviations (points with error bars) of the baseline thyroid cancer incidence; a) girls, b) boys. The lines represent analytical fits according to eq. (9).

Fig. 5. Annual total and baseline number of thyroid cancer cases in the birth cohort 1968-85 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.

Table 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.

Study	Area	Age group	Period	Number of cases	Prevalence (cases per 10^6 persons)
IPHECA (7)	Gomel (Bel)	ATA ≤ 18	1990-1992	15	2200
	Kyiv and Zhytomyr (Ukr)	ATS ≤ 15	1992-1994	5	400
Sasakawa (8–10)	Gomel (Bel)	ATA ≤ 9	1991-1996	37	1900
	Mogilev (Bel)	ATA ≤ 9	1991-1996	2	80
	Kyiv (Ukr)	ATA ≤ 18	1996-2000	25	2300
	Zhytomyr (Ukr)	ATA ≤ 14	1996-2000	11	1300
Belarus screening programme (11, 12)	Belarus	ATS ≤ 14	1990-1991	7	6400
	Gomel (Bel)	ATS ≤ 18	2002	2	53
Ukraine-USA cohort study (13)	Kyiv, Chernihiv and Zhytomyr (Ukr)	ATA ≤ 18	1998-2000	43	3200
			2001-2002	21	1800

Table 2. Number of personsyears and of thyroid cancer cases (in the period 1986–2001) in the birth cohort 1968–85 in Belarusian (bold) and Ukrainian oblasts and cities.

Region	10^6 personyears		Cases		Region	10^6 personyears		Cases	
	male	female	male	female		male	female	male	female
Brest	3.12	3.05	105	191	Kirovohrad	2.39	2.30	9	38
Gomel City	1.07	1.04	51	125	Kyiv City	5.57	5.43	70	235
Gomel Oblast	2.49	2.49	217	332	Kyiv Oblast	3.89	3.80	78	209
Grodno	2.32	2.26	32	51	Luhansk	5.60	5.43	9	45
Minsk City	3.37	3.22	40	115	Lviv	6.12	5.78	16	62
Minsk Oblast	3.26	3.15	31	74	Mykolaiv	2.75	2.72	6	23
Mogilev	2.64	2.64	32	118	Odesa	5.42	5.26	8	66
Vitebsk	2.73	2.69	11	57	Poltava	3.28	3.20	9	45
Cherkasy	2.89	2.85	15	49	Rivne	2.72	2.58	21	51
Chernihiv	2.54	2.44	42	100	Sevastopol	0.84	0.81	1	12
Chernivtsi	2.12	2.07	6	26	Sumy	2.70	2.66	8	27
Crimea	5.11	4.85	8	43	Ternopil	2.42	2.31	0	5
Dnipropetrovsk	7.74	7.68	29	128	Vinnytsia	3.73	3.58	26	82
Donetsk	10.29	10.02	41	125	Volyn	2.40	2.28	6	16
Ivano-Frankivsk	3.18	3.03	7	21	Zakarpattia	3.08	2.96	3	15
Kharkiv	6.30	6.14	18	92	Zaporizhzhia	4.14	4.12	19	58
Kherson	2.67	2.62	17	78	Zhytomyr	3.21	3.05	41	83
Khmelnytsk	3.07	2.86	10	35					

Table 3. Estimates of the excess absolute risk per dose, *α*, and the excess relative risk per dose, *β*, for the incidence of thyroid cancer after exposures during childhood or adolescence. Best estimates and 95 percent confidence intervals are given.

Exposure pathway	Age at exposure	Reference	α $(10^4\ \text{PY-Gy})^{-1}$		β (Gy^{-1})	
External	0-14	Ron et al. (23)	4.4	1.9, 10.1	7.7	2.1, 28.7
Chernobyl	0.3-15.3	Jacob et al. (15)	2.1	1.0, 4.5	23	8.6, 82
Chernobyl	0-15.3	Likhtarev et al. (14)	1.6	0.7, 3.4	38.5*	16.4, 96.8
Chernobyl	0-18.3	Kenigsberg et al. (5)	1.93	1.79, 2.06	37.7*	35.1, 40.2

* Estimate of relative risk may be biased because of underestimation of baseline incidence.

Table 4. Grouping of Ukrainian and Belarusian (bold) oblasts according to baseline thyroid cancer incidence rates as calculated with eq. (6).

Baseline incidence rate larger than 10.5 cases per 10^6 PY	Intermediate baseline incidence rate	Baseline incidence rate smaller than 2.9 cases per 10^6 PY
Chernihiv*	Chernivtsi	Cherkasy
Kherson	Dnipropetrovsk	Crimea
Kyiv City*	Donetsk	Ivano-Frankivsk
Kyiv Oblast*,**	Kharkiv	Kirovohrad
Vinnytsia	Khmelnytsk	Luhansk
Brest	Lviv	Mykolaiv
Gomel City*	Odesa	Rivne
Gomel Oblast*,**	Poltava	Sevastopol
Grodno	Zaporizhzhia	Sumy
Minsk Oblast*,**	Zhytomyr*	Ternopil
Mogilev*	**Minsk City***	Volyn
Vitebsk		Zakarpattia

* Oblast/city with measurements of ^{131}I activity in human thyroids
** Oblast without capital

Table 5. Oblasts/cities that change compared to Table 4 the group of baseline incidence if eq. (7) is used instead of eq. (6) for the grouping, or if the radioecological model is used for dose estimations in Belarus.

Dose	Grouping	Oblasts/cities in other groups than for main results
As for main results	Eq. (7)	upper: - medium: Luhansk, Mykolaiv lower: Poltava, Zhytmomyr
Radioecological model for Belarus	Eq. (6)	upper: Minsk City medium: Vinnytsia lower: -

Table 6a. Thyroid cancer cases among the female birth cohort 1968-85 in groups of oblasts and cities as defined in Table 4. Poisson regressions were performed for classes with bold case numbers.

Region	Age at operation	1986-89	1990-93	1994-97	1998-2001	1986-2001
		Females				
Upper group	1 – 4	**1**	0	0	0	1
	5 – 9	**4**	**42**	6	0	52
	10 – 14	**7**	**65**	**142**	32	246
	15 – 19	**19**	**44**	**105**	**149**	317
	20 – 24	2	**52**	**96**	**138**	288
	25 – 29	0	5	**113**	**198**	316
	30 – 33	0	0	0	**100**	100
	1 – 33	33	208	462	617	1320
Middle group	1 – 4	**1**	0	0	0	1
	5 – 9	**2**	**40**	6	0	48
	10 – 14	**10**	**50**	**100**	26	186
	15 – 19	**31**	**35**	**70**	**139**	275
	20 – 24	2	**76**	**89**	**111**	278
	25 – 29	0	4	**119**	**158**	281
	30 – 33	0	0	0	**98**	98
	1 – 33	46	205	384	532	1167
Lower group	1 – 4	**0**	0	0	0	0
	5 – 9	**1**	**10**	0	0	11
	10 – 14	**7**	**18**	**19**	6	50
	15 – 19	**9**	**12**	**24**	**29**	74
	20 – 24	2	**18**	**22**	**51**	93
	25 – 29	0	2	**27**	**53**	82
	30 – 33	0	0	0	**35**	35
	1 – 33	19	60	92	174	345

Table 6b. Thyroid cancer cases among the male birth cohort 1968-85 in groups of oblasts and cities as defined in Table 4. Poisson regressions were performed for classes with bold case numbers.

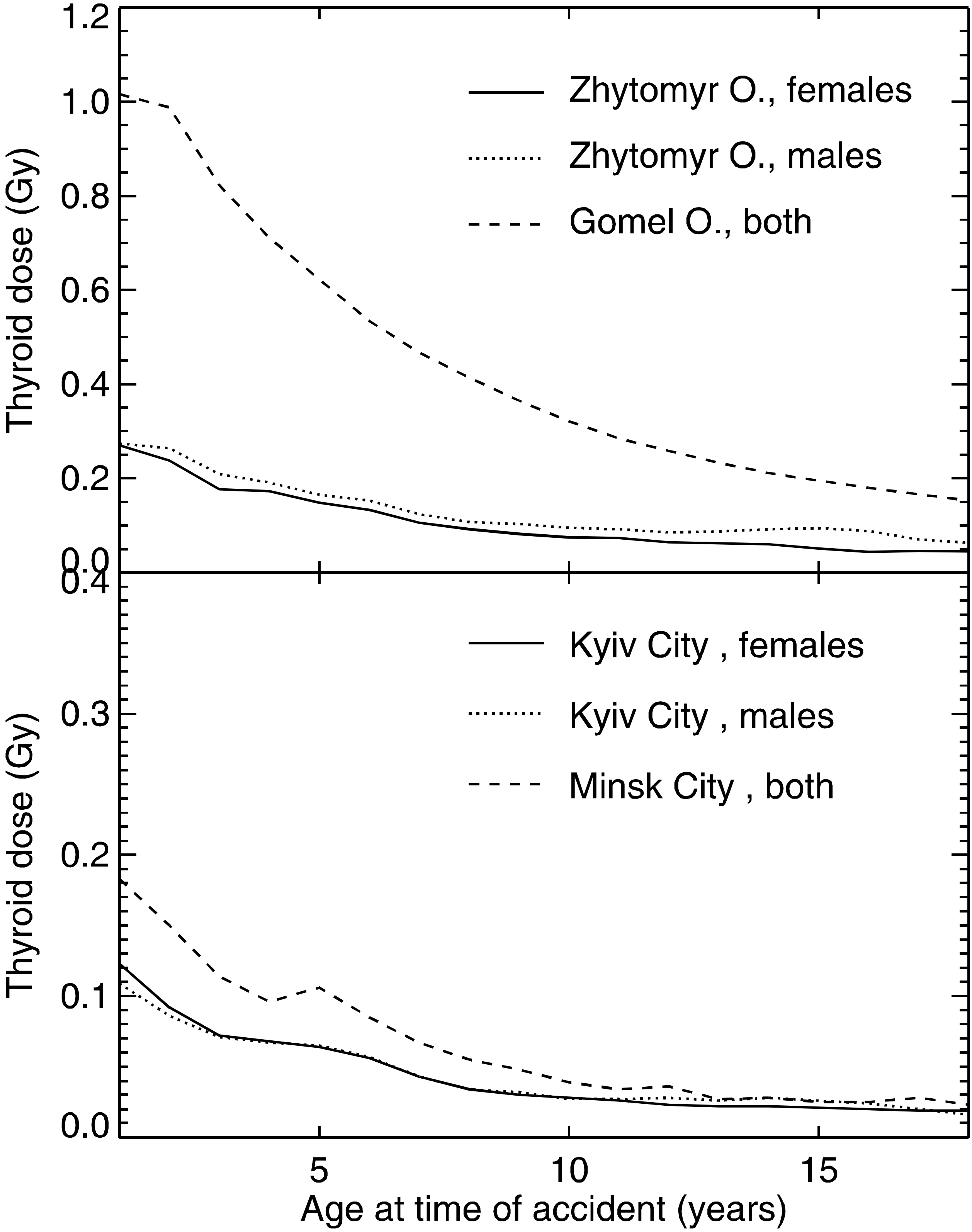
Region	Age at operation	Operation year 1986-89	1990-93	1994-97	1998-2001	1986-2001
		Males				
Upper group	1 – 4	**1**	0	0	0	1
	5 – 9	**1**	**32**	8	0	41
	10 – 14	**7**	**39**	**78**	21	145
	15 – 19	**8**	**19**	**34**	**86**	147
	20 – 24	2	**12**	**18**	**36**	68
	25 – 29	0	0	**23**	**44**	67
	30 – 33	0	0	0	**26**	26
	1 – 33	19	102	161	213	495
Middle group	1 – 4	**1**	0	0	0	1
	5 – 9	**3**	**27**	6	0	36
	10 – 14	**8**	**24**	**59**	14	105
	15 – 19	**8**	**27**	**36**	**69**	140
	20 – 24	2	**11**	**28**	**39**	80
	25 – 29	0	1	**22**	**43**	66
	30 – 33	0	0	0	**26**	26
	1 – 33	22	90	151	191	454
Lower group	1 – 4	**0**	0	0	0	0
	5 – 9	**1**	**5**	0	0	6
	10 – 14	**1**	**6**	**10**	1	18
	15 – 19	**1**	**7**	**12**	**10**	30
	20 – 24	0	**3**	**5**	**9**	17
	25 – 29	0	1	**5**	**12**	18
	30 – 33	0	0	0	**4**	4
	1 – 33	3	22	32	36	93

Table 7. Best estimates of parameter values c_{lsn} and d_{lsn} in eq. (9), the best estimate of e_{female} is 2.8 and of e_{male} 2.1.

Sex, Calendar year period	$c_{lsn}(10^6$ PY)			$d_{lsn}(10^6$ PY)		
	Lower group	Middle group	Upper group	Lower group	Middle group	Upper group
Females						
1986 - 1989	0.18	0.06	0.00	$6.4\ 10^{-4}$	$1.8\ 10^{-3}$	$2.3\ 10^{-3}$
1990 - 1993	0.83	0.00	4.13	$1.1\ 10^{-3}$	$3.0\ 10^{-3}$	$3.4\ 10^{-3}$
1994 - 1997	2.93	0.00	4.14	$5.6\ 10^{-4}$	$3.2\ 10^{-3}$	$5.6\ 10^{-3}$
1998 - 2001	6.04	4.11	6.23	$7.5\ 10^{-4}$	$2.3\ 10^{-3}$	$4.9\ 10^{-3}$
Males						
1986 - 1989	0.07	0.45	0.48	$1.5\ 10^{-03}$	$5.0\ 10^{-3}$	$8.4\ 10^{-3}$
1990 - 1993	0.00	0.29	1.66	$1.8\ 10^{-3}$	$5.6\ 10^{-3}$	$7.0\ 10^{-3}$
1994 - 1997	1.24	0.00	6.03	0.0	$4.1\ 10^{-3}$	$1.1\ 10^{-3}$
1998 - 2001	0.70	0.00	0.00	$1.3\ 10^{-3}$	$3.9\ 10^{-3}$	$9.1\ 10^{-3}$


N
W
E
S
Vitebsk
Minsk Oblast
Minsk City
Grodno
Mogilev
Belarus
Brest
Gomel City
Gomel Oblast
Volyn
Rivne
Chernihiv
Sumy
Zhytomyr
Kyiv City
Kyiv Oblast
Lviv
Ternopil
Poltava
Kharkiv
Ukraine
Ivano-Frankivsk
Khmelnytsk
Vinnitsia
Cherkasy
Luhansk
Zakarpattia
Chernivtsi
Kirovohrad
Dnipropetrovsk
Donetsk
Mykolaiv
Zaporizhzha
Kherson
Odesa
Crimea
Sevastopol
100 50 0 100 200 300 400
km

Fig. 1



Zhytomyr O., females
Zhytomyr O., males
Gomel O., both
Thyroid dose (Gy)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Kyiv City , females
Kyiv City , males
Minsk City , both
Thyroid dose (Gy)
0.4
0.3
0.2
0.1
0.0
5
10
15
Age at time of accident (years)

Fig. 2

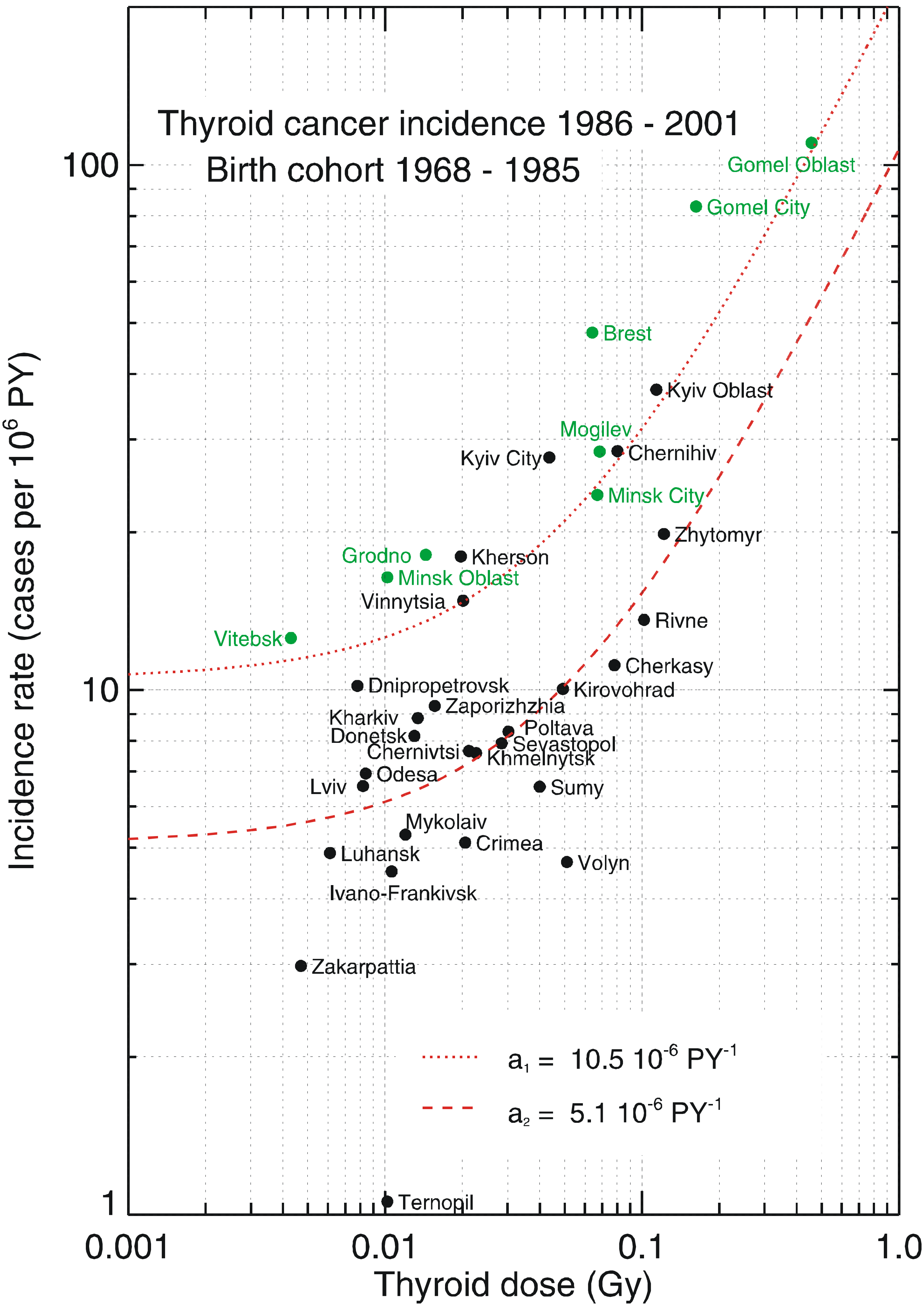

Thyroid cancer incidence 1986 - 2001
Birth cohort 1968 - 1985
Incidence rate (cases per 10⁶ PY)
Thyroid dose (Gy)
100
10
1
0.001
0.01
0.1
1.0
Gomel Oblast
Gomel City
Brest
Kyiv Oblast
Mogilev
Kyiv City
Chernihiv
Minsk City
Zhytomyr
Grodno
Kherson
Minsk Oblast
Vinnytsia
Rivne
Vitebsk
Cherkasy
Dnipropetrovsk
Kirovohrad
Zaporizhzhia
Kharkiv
Donetsk
Poltava
Sevastopol
Chernivtsi
Khmelnytsk
Odesa
Lviv
Sumy
Mykolaiv
Crimea
Luhansk
Volyn
Ivano-Frankivsk
Zakarpattia
Ternopil
a₁ = 10.5 10⁻⁶ PY⁻¹
a₂ = 5.1 10⁻⁶ PY⁻¹

Fig. 3

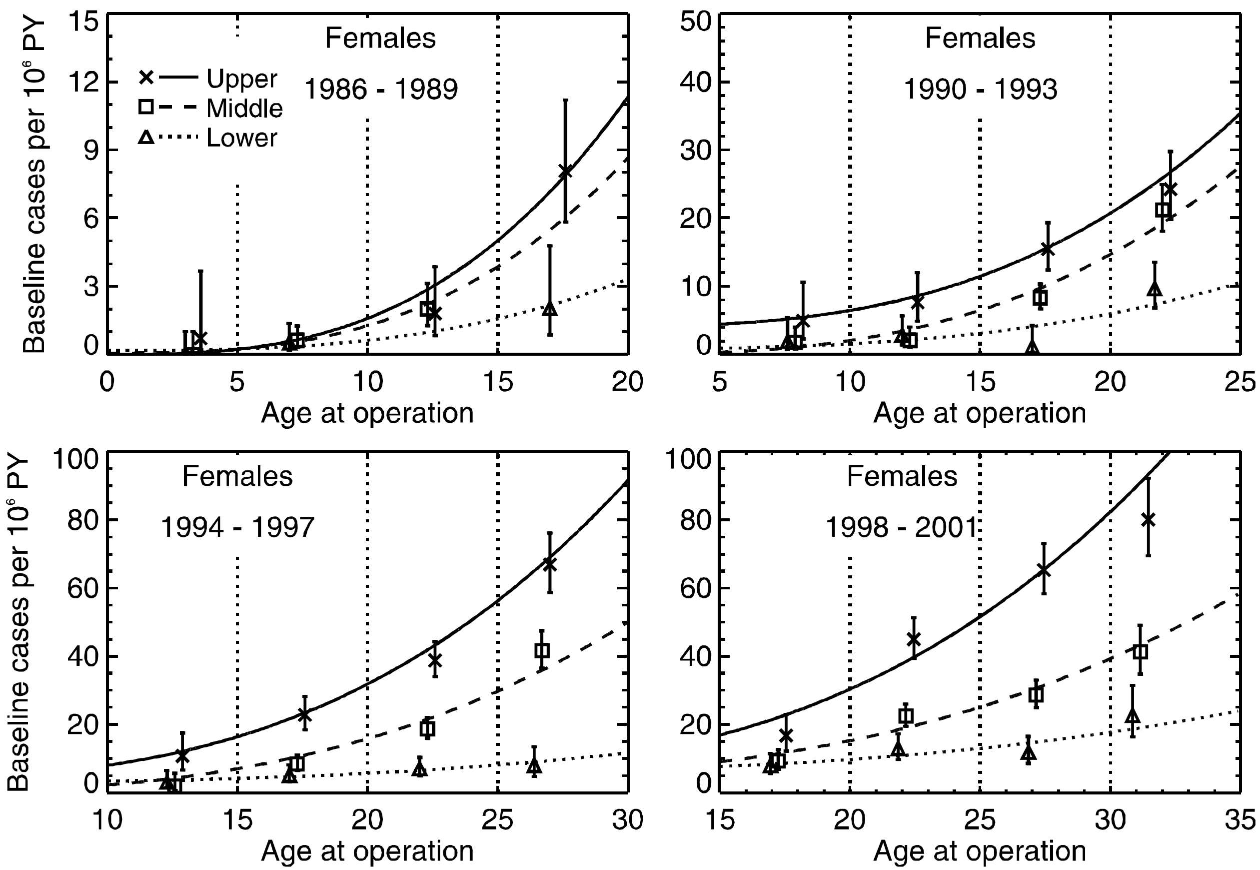

Females
1986 - 1989
Upper
Middle
Lower
Baseline cases per 10^6 PY
Age at operation
Females
1990 - 1993
Females
1994 - 1997
Females
1998 - 2001

Fig. 4a

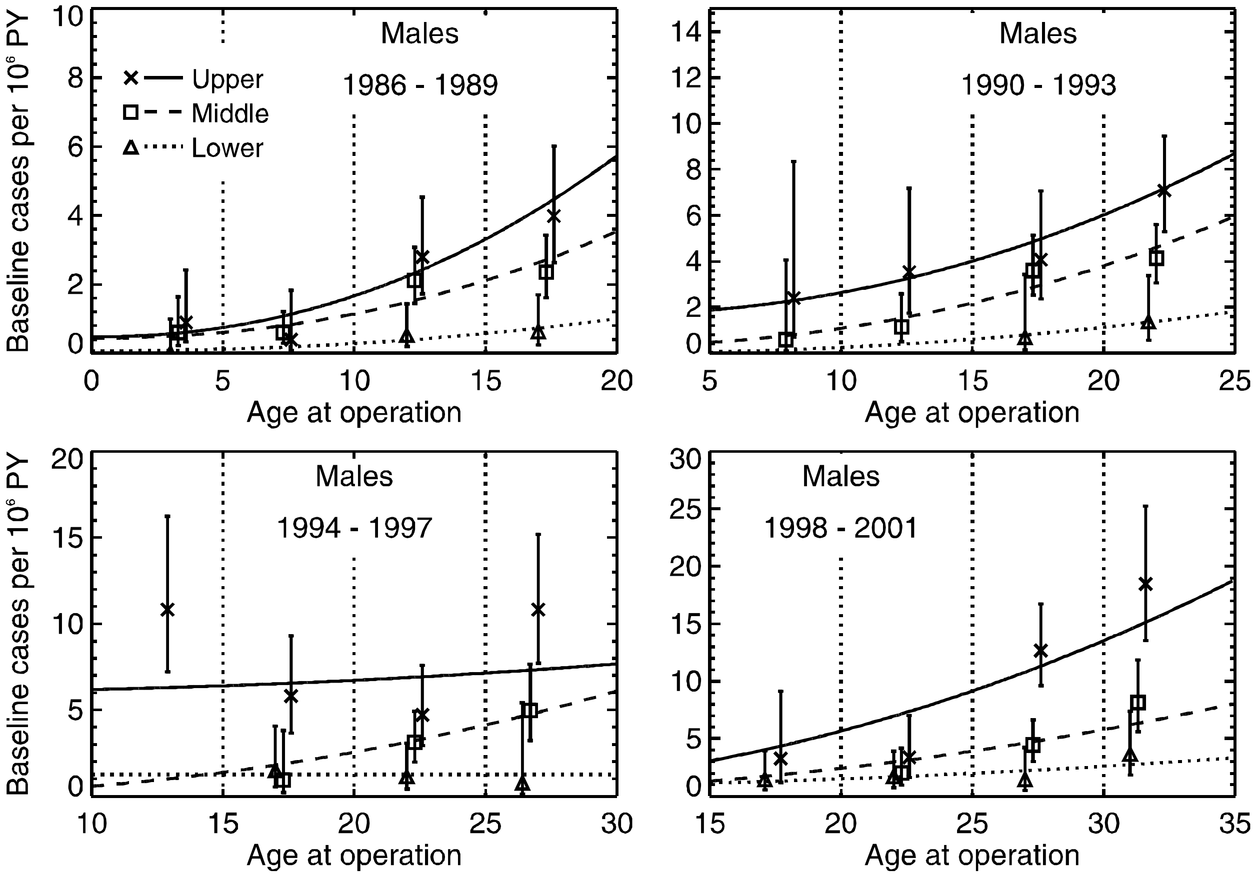

Males
1986 - 1989
Upper
Middle
Lower
Baseline cases per 10⁶ PY
Age at operation
Males
1990 - 1993
Age at operation
Males
1994 - 1997
Baseline cases per 10⁶ PY
Age at operation
Males
1998 - 2001
Age at operation

Fig. 4b

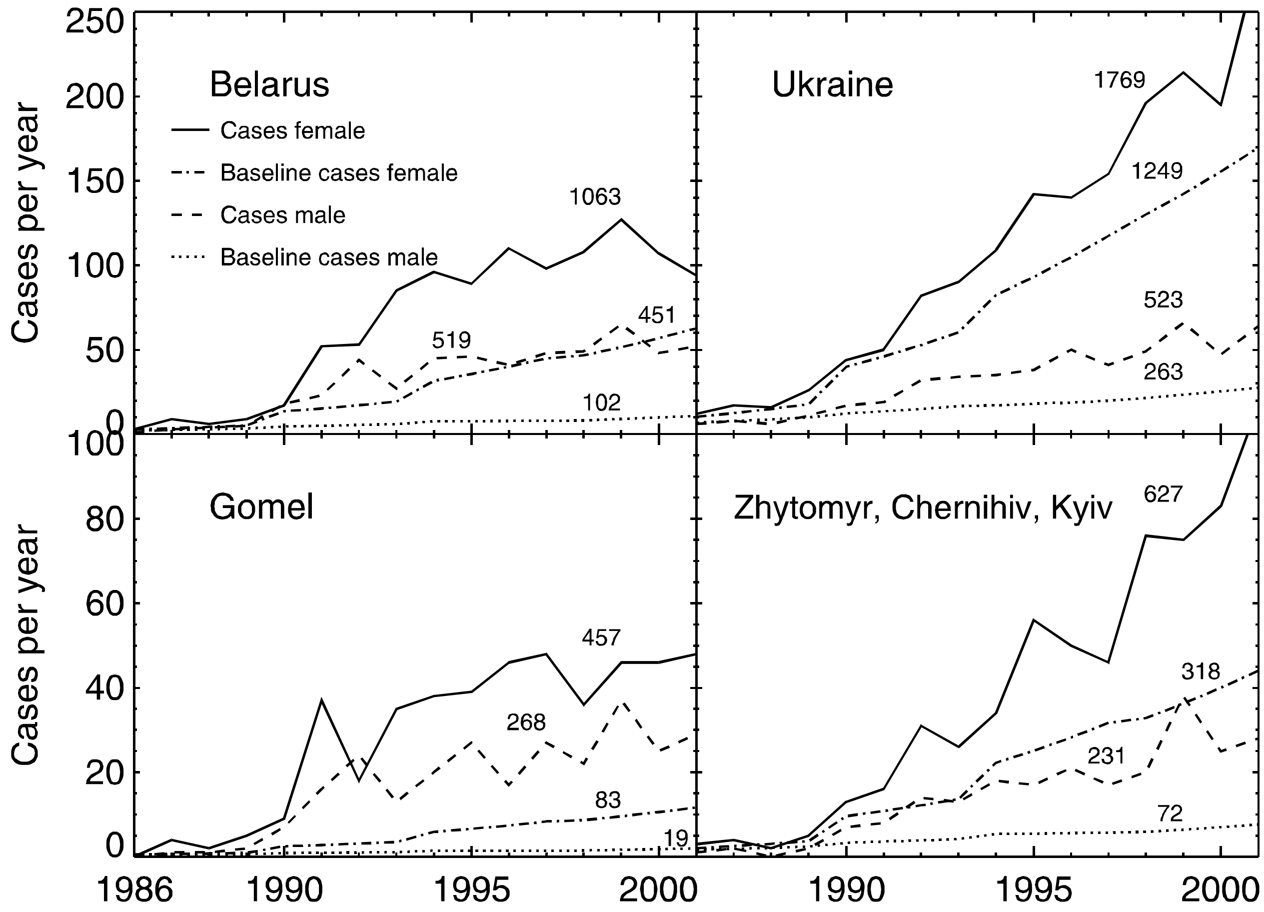

Belarus
Cases female
Baseline cases female
Cases male
Baseline cases male
1063
519
451
102
Ukraine
1769
1249
523
263
Gomel
457
268
83
19
Zhytomyr, Chernihiv, Kyiv
627
318
231
72
Cases per year
Cases per year
250
200
150
100
50
0
100
80
60
40
20
0
1986
1990
1995
2000
1990
1995
2000

Fig. 5