Appendix 11

Thyroid Cancer Excess Risks in Ukrainian and Belarusian Areas Affected by the Chernobyl Accident

Thyroid Cancer Risk

in Ukrainian and Belarusian Areas Affected by the Chernobyl Accident

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Jacob, P., Kenigsberg, J., Likhtarev, I., Tronko, M., Shinkarev, S., Schotola, C., Kovgan, L, Bogdanova, T. and Gavrilin Y. Thyroid cancer risk in Ukrainian and Belarusian areas and Ukraine affected by the Chernobyl accident.

ABSTRACT

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 1968-85. Census data from 1979 and 1989, and mortality rates in the period 1986-89 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.

INTRODUCTION

The thyroid cancer incidence in Ukraine and in Belarus started to increase significantly in 1990 among those who were children or adolescents at the time of the Chernobyl accident in April 1986 (Kazakov et al. 1992, Likhtarev et al. 1995). Since then, the incidence rate is further increasing (Tronko et al. 1999, Demidchik and Demidchik 2002).

In each of both countries, more than 100 000 measurements of the ^{131}I content in human thyroids have been measured in May/June 1986. Based on these data, thyroid doses of the population in the highly contaminated areas have been estimated (Likhtariov et al. 1993, Gavrilin et al. 1999).

Population, average dose and case data were used in 'ecologic' analyses to derive estimates of excess thyroid cancer risks (*e.g.*, Jacob et al. 1999, Likhtarev et al. 1999, Kenigsberg et al. 2002). There is a general concern whether quantitative risk values can be derived with such an ecologic study design (*e.g.*, Morgenstern 1998, Lubin 2002). Extensive simulation studies have therefore been performed in order to explore this question for the thyroid cancer incidence in areas highly contaminated by the Chernobyl accident (Kaiser et al. 2004). The results of these simulation studies indicate that the ecologic bias is relatively small in studies in which the ecologic units are age groups in settlements with measurements of the ^{131}I content in the human thyroid. The reasons are:

- 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
- according to the available information (Ron et al. 1995, Jacob et al. 1999), 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

Simulations of possible correlations between dose and screening showed only a small bias of estimates of the excess absolute risk (there was, however, in some scenarios a bias of the estimate of the relative risk. Also, simulations of selecting parts of the population for measurement of the ^{131}I content in the human thyroid showed only a small bias of risk estimates in the simulated ecologic studies.

It is the purpose of this paper to derive risk estimates for those who were at the time of the Chernobyl accident children or adolescents in settlements, in which more than 10 measurements of the ^{131}I content in the human thyroid have been performed in May/June 1986. The risk analysis is based on improved dose estimates (Appendices 1, 2 and 3) and performed for the period 1990 to 2001.

METHODS AND MATERIALS

The present study uses data for 684 settlements in Ukraine and 458 settlements in Belarus (Fig. 1). Basic data used here for the two genders in the single birth-year cohorts 1968 – 85 are

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

In total, the study comprises 41 112 ecologic units (1142 settlements, 18 age-at-exposure groups, 2 genders), and about 250 000 measurements of the ^{131}I activity in human thyroids were used to derive average doses in these ecologic units.

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 Appendix 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), up to 17 Gy for 1-year old boys.

Belarus. Two different methodologies of deriving age-dependent thyroid doses, as described in Appendices 2 and 3, 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. For the present analysis, the gender ratio of the doses in Kyiv City, which was the Ukrainian city with the largest number of ^{131}I measurements, was used to derive gender-specific doses $D_{s,i}^{city}$ for the birth cohort i in Minsk and Gomel City according to

$$D_{s,i}^{city} = D_{av,i}^{city} \cdot D_{s,i}^{K} / D_{av,i}^{K} , \qquad (1)$$

with

$$D^{K}_{av,i} = (PY^{K}_{f,i} D^{K}_{f,i} + PY^{K}_{m,i} D^{K}_{m,i}) / (PY^{K}_{f,i} + PY^{K}_{m,i}),$$

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 other settlements of Belarus were derived using the gender-ratio of the doses in Chernihiv Oblast, which was the Ukrainian oblast with the largest number of ^{131}I measurements.

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 19 Gy for 1-year old boys according to the FENIX methodology (Appendix 2), and up to 17 Gy according to the GSF methodology (Appendix 3).

Both countries. For settlements close to the boundary of the two countries, comparable values have been derived by the dosimetric approaches in the two countries (Fig. 1). In total, the study comprises 41 112 ecologic units (1142 settlements, 18 age-at-exposure groups, 2 genders), and about 250 000 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). The ratio of the two percentiles is 40, for a lognormal distribution this corresponds to a geometric standard deviation (GSD) of 2.5. It is an important criterion for the evaluation of the ecologic study to compare this range of the doses in the ecologic units with the range of doses within the single ecologic units.

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.

In Appendix 3 it has been assessed that the distribution of the individual doses in each of the groups may be characterised by a GSD of 2.0. In summary, the variability of the true individual doses in the single age-gender classes in each of the settlements can in general be assumed to be smaller than the variability of the average values of the ecologic units.

Population data

Ukraine. The main sources of information on the age-gender structure of the Ukrainian population were the All-Union (Former Soviet Union) census data for the years 1979 and 1989 (USSR State Committee 1989, Ministry of Statistics of Ukrainian SSR 1991). The data include the age-gender structure of the urban and rural population in each of the Ukrainian oblasts. Age-gender specific death rates (Technika 1991, Statistics State Committee of Ukraine) were used to derive from the 1989 data the population in 1986. A linear interpolation of the census data for 1979 and 1989 gave similar results.

Information on the total population of the settlements in the northern oblasts in the years 1992 - 94 was obtained from local authorities. Information on the population in the Ukrainian oblasts for 1991 and 1994 was received from the Ministry of Statistics of Ukraine. It was assumed that the number of population of each settlement changed during 1986-1994 proportionally to the changes of the whole rural / urban population of the oblast, in which the settlement is located, and that also the age-gender structure is the same.

In total, there were 1005 thousand children and adolescents in 1986 in the 36 age- and gender groups of the 684 Ukrainian settlements. Most of the children and adolescents lived in Kyiv. High doses occurred mainly in small settlements (Fig. 3).

Belarus. The age-gender structure of the population in the settlements in 1986 was estimated on the basis of census data for the total number of inhabitants in 1989. The following algorithm was used (Kenigsberg et al. 2002):

- Design of the one-year age-gender structure of the oblasts based on the census data for 1989;
- Calculation of the age-gender structure of the settlement inhabitants for 1989 by scaling the age-gender structure of the oblast by the total number of people in the settlement;
- Transition from the gender-age structure of every settlement inhabitants in 1989 to the gender-age structure in 1986 by the use of age-gender specific death-rate in 1986-88.

Reports of the statistical offices of the Ministry of Health of the Belarusian SSR from 1986 were used to verify of derived population of selected settlements.

In total, there were 629 thousand children and adolescents in 1986 in the 36 age- and gender groups of the 458 settlements. Most of the children and adolescents lived in Minsk. High doses occurred as in Ukraine mainly in small settlements (Fig. 3).

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 1968-85 in the 684 Ukrainian settlements, 379 cases among females and 135 for males. There is only a modest dependence on birth year (Fig. 4).

The incidence rate is for the youngest (birth years 1982-85) 52 cases per 10^6 person-years, for the 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).

The incidence rate in the birth cohort 1968-85 of the 684 Ukrainian settlements increases linearly since 1990 (Fig. 5).

Belarus. The thyroid cancer registry and morphological characteristics of the cases are described in Section 3.2. In total, 581 thyroid cancer cases have been reported for the period 1990-2001 and the birth-year cohort 1968-85 in the 485 Belarusian settlements, 370 cases among females and 211 for males.

The incidence rate is for the youngest (birth years 1984-85) 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 1978-69. The ratio of female to male cases is about 1.6 for the youngest ones (1980-85), 1.2 for the birth-year cohort (1976-79), and increases to 4 for the older ones (birth years 1968-71).

The incidence rate in the 458 Belarusian settlements started to increase steeply in 1990 (Fig. 5). In contrast to the Ukrainian, the increase rate was not constant over the whole period up to 2001. It became smaller in the middle of the 90ies.

Analysis of data

Poisson regressions were performed with the excess absolute risk model

$$\lambda(d) = \exp(\beta_0) + \beta_1 \cdot d, \quad (2)$$

with the excess relative risk model

$$\lambda(d) = \exp(\beta_0)(1 + \beta_1 \cdot d), \quad (3)$$

and with a quadratic model

$$\lambda(d) = \exp(\beta_0) + \beta_1 \cdot d + \beta_2 \cdot d^2, \quad (4)$$

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) in the period 1990-2001 for the birth cohort 1968-85 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 estimates for Ukraine (Table 1) 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 (Table 2). 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 (Table 3). 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 1990-93. The difference is significant ($p < 0.04$). For Ukraine, the EAR per dose is not significant for the period 1990–93 of operation years.

Whereas for the younger ones the EAR per dose increases compared to the period 1990–93 considerably already in the period 1994–97, a much smaller age-after-exposure effect is observed for the 7-12 years olds at exposure (Table 4). For the older ones, no significant results were obtained for the first two time periods, but the best estimates indicate a strong increase with time after exposure. In summary, no clear picture of the time-after-exposure dependence for the different age-at-exposure groups could be obtained.

Shape of dose response. In general, the best estimate of the quadratic term according to eq. (4) is negative and contributes less than 8% to the EAR at thyroid doses of 1 Gy (Table 5). 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 1968-85 in all 1142 settlements is for females to 6.6 (95% CI: 4.9; 8.4) Gy^{-1}, and for males to 36 (95% CI: 14; 58) Gy^{-1} (Table 1). 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. Therefore, only selected resulted on dependencies on age at exposure or time after exposure are reported here for Ukraine and Belarus together.

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 (Table 6). The best estimate of the ERR per dose is larger by a factor of 2.3 – 2.6 for the period 1990 - 93 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 analysis presented here does not take into account dose uncertainties. The uncertainty of the average dose estimates for settlements in Belarus has been estimated by two different methods.

In Section 2.2.2, a factorisation method has been applied in order to derive dose estimates as a product of the average dose in a settlement, and an age-dependent factor. The average of the coefficient of variation of the average dose in the Belarusian settlements was 0.5. Assuming a lognormal distribution this corresponds to a GSD of 1.6.

In Section 2.3, a variogram representing the variance of average thyroid doses as a function of the distance between pairs of settlements has been derived. This variation is due to the spatial variation of the radioecological conditions and to the variance of the mean thyroid doses in the settlements. The variance of the dose due to the latter effect was estimated to be about 0.16. For a lognormal distribution this corresponds to a GSD of 1.5.

The results of the two estimates of uncertainties of the average dose in Belarusian settlements are quite close. The second one is possibly a bit smaller, because due to local correlations (*e.g.*, same measurement teams in adjacent settlements) the variability of dose estimates in adjacent settlements is smaller than the dose uncertainty.

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 (Caroll et al. 1995). There are two indications, however, that this underestimation is small for the current analysis.

- The dose uncertainty (GSD of about 1.5) is small compared to the range of average doses used in the Poisson regression (GSD of about 2.5, see section Thyroid doses in chapter Materials and Methods).
- 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 the dose uncertainties 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 chapter 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 1991–95 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 be in the period 1994–96 by a factor of 1.5 higher than in the period 1991–93.

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.

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Figure legends

Fig. 1. 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 human thyroids have been performed in May/June 1986.

Fig. 2. 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.

Fig. 3. Number of children and adolescents in 1986, and their average thyroid dose in 684 Ukrainian and 458 Belarusian settlements.

Fig. 4. Thyroid cancer cases in the period 1990-2001 in 684 Ukrainian and 458 Belarusian settlements in dependence of the birth-year.

Fig. 5. Thyroid cancer cases among the birth-year cohort 1968-85 in 684 Ukrainian and 458 Belarusian settlements in dependence of the operation year.

Table 1. Excess risk estimates (best estimates and 95% confidence intervals) for the thyroid cancer incidence in the period 1990 – 2001 and the birth-year cohort 1968-85 in 684 Ukrainian and 458 Belarusian settlements.

Area/dosimetry	EAR per dose $(10^4 \text{ PY Gy})^{-1}$			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; 3.5)	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)

Table 2. EAR per dose (best estimates and 95% confidence intervals) for the thyroid cancer incidence in the period 1990 – 2001 in 684 Ukrainian and 458 Belarusian settlements.

Birth-year cohort	Area/dosimetry	Excess absolute risk per dose (10^4 PY-Gy)$^{-1}$		
		females	males	both
1968-73	Ukraine	1.5 (-0.9; 3.9)	0.5 (-0.4; 1.4)	0.6 (-0.4; 1.6)
1974-79		2.9 (0.9; 4.9)	1.3 (0.2; 2.4)	1.9 (0.9; 3.0)
1980-85		2.7 (1.6; 3.8)	1.9 (1.0; 2.7)	2.3 (1.6; 2.9)
1968-73	Belarus/GSF	2.4 (0.6; 4.1)	1.5 (0.4; 2.6)	1.8 (0.8; 2.8)
1974-79		2.3 (1.1; 3.6)	3.2 (2.3; 4.0)	3.0 (2.2; 3.9)
1980-85		5.6 (4.5; 6.7)	3.0 (2.5; 3.6)	4.1 (3.6; 4.5)
1968-73	Belarus/FENIX	2.1 (0.5; 3.7)	1.4 (0.4; 2.4)	1.6 (0.7; 2.5)
1974-79		2.4 (1.2; 3.6)	3.1 (2.3; 4.0)	3.0 (2.2; 3.9)
1980-85		5.1 (4.0; 6.1)	2.8 (2.3; 3.3)	3.8 (3.4; 4.3)
1968-73	Ukraine and Belarus/GSF	2.3 (0.8; 3.7)	1.1 (0.4; 1.9)	1.4 (0.7; 2.2)
1974-79		2.4 (1.4; 3.4)	2.6 (1.8; 3.4)	2.6 (1.9; 3.2)
1980-85		4.5 (3.7; 5.2)	2.7 (2.4; 3.1)	3.6 (3.1; 4.1)
1968-73	Ukraine and Belarus/FENIX	2.1 (0.8; 3.4)	1.1 (0.4; 1.8)	1.4 (0.7; 2.0)
1974-79		2.4 (1.4; 3.4)	2.6 (1.8; 3.4)	2.5 (1.9; 3.2)
1980-85		4.1 (3.4; 4.9)	2.6 (2.3; 3.0)	3.4 (2.9; 3.8)

Table 3. EAR per dose (best estimates and 95% confidence intervals) for the thyroid cancer incidence of the birth cohort 1968 - 85 in 684 Ukrainian and 458 Belarusian settlements.

Period of operation year	Area/dosimetry	Excess absolute risk per dose $(10^4 \text{ PY-Gy})^{-1}$		
		females	males	both
1990-93	Ukraine	0.8 (-0.1; 1.7)	0.3 (-0.2; 0.8)	0.5 (0.0; 1.0)
1994-97		2.3 (0.9; 3.7)	1.6 (0.7; 2.4)	1.9 (1.1; 2.6)
1998-2001		2.9 (1.2; 4.5)	2.4 (1.3; 3.6)	2.6 (1.6; 3.5)
1990-93	Belarus/GSF	2.9 (1.9; 3.9)	2.1 (1.5; 2.7)	2.5 (1.9; 3.1)
1994-97		4.0 (2.8; 5.3)	2.9 (2.2; 3.6)	3.5 (2.7; 4.2)
1998-2001		4.4 (3.0; 5.7)	3.6 (2.6; 4.6)	4.0 (3.2; 4.8)
1990-93	Belarus/FENIX	2.6 (1.7; 3.5)	2.0 (1.3; 2.7)	2.3 (1.7; 2.9)
1994-97		3.6 (2.4; 4.8)	2.8 (2.2; 3.5)	3.2 (2.5; 3.9)
1998-2001		4.0 (2.8; 5.3)	3.3 (2.4; 4.2)	3.6 (2.9; 4.4)
1990-93	Ukraine and Belarus/GSF	2.7 (1.8; 3.5)	1.8 (1.2; 2.4)	2.2 (1.7; 2.7)
1994-97		4.5 (3.3; 5.6)	3.0 (2.2; 3.7)	3.6 (3.0; 4.3)
1998-2001		4.5 (3.3; 5.8)	3.8 (2.9; 4.7)	4.1 (3.4; 4.9)
1990-93	Ukraine and Belarus/FENIX	2.1 (1.4; 2.7)	1.4 (1.0; 1.9)	1.7 (1.3; 2.1)
1994-97		3.4 (2.5; 4.3)	2.4 (1.8; 3.0)	2.8 (2.3; 3.4)
1998-2001		3.5 (2.5; 4.4)	3.0 (2.3; 3.7)	3.1 (2.6; 3.7)

Table 4. EAR per dose (best estimates and 95% confidence intervals) for the thyroid cancer incidence in 684 Ukrainian and 458 Belarusian settlements, based on the GSF estimates of thyroid doses.

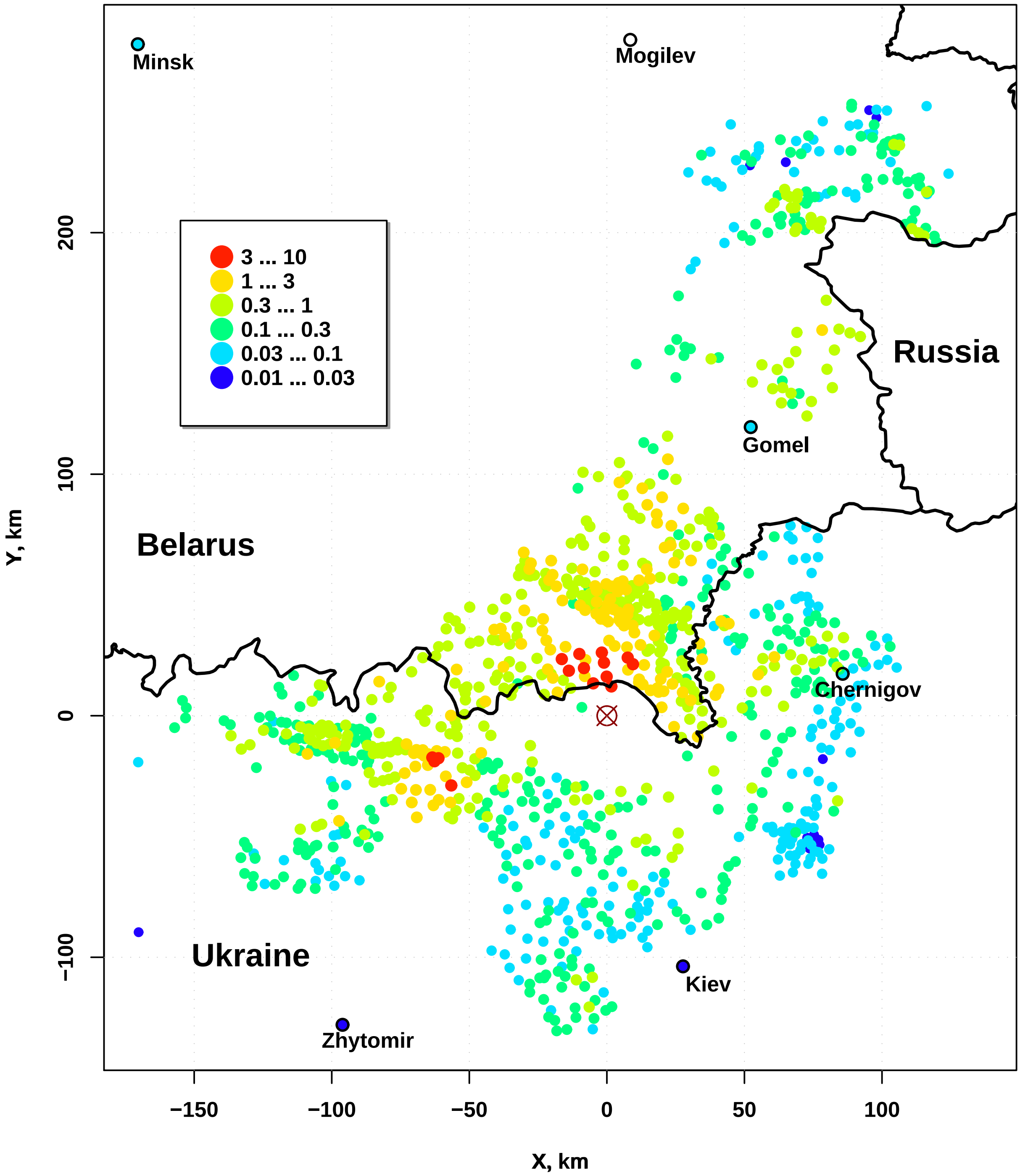
Period of operation year	Birth-year cohort	Excess absolute risk per dose $(10^4 \text{ PY-Gy})^{-1}$		
		females	males	both
1990-93	1968-73	0.3 (-0.9; 1.5)	0.1 (-0.4; 0.7)	0.1 (-0.4; 0.7)
1994-97	1968-73	1.7 (-0.5; 4.0)	0.7 (-0.3; 1.7)	0.9 (-0.1; 2.0)
1998-2001	1968-73	4.5 (1.2; 7.9)	2.5 (0.6; 4.3)	3.1 (1.4; 4.9)
1990-93	1974-79	2.6 (0.9; 4.3)	2.3 (1.0; 3.6)	2.4 (1.4; 3.5)
1994-97	1974-79	1.8 (0.3; 3.4)	1.6 (0.5; 2.7)	1.8 (0.9; 2.8)
1998-2001	1974-79	2.9 (0.9; 4.9)	3.9 (2.2; 5.6)	3.5 (2.1; 4.8)
1990-93	1980-85	2.7 (2.0; 3.4)	1.5 (1.0; 2.0)	2.1 (1.7; 2.5)
1994-97	1980-85	5.4 (4.0; 6.8)	3.1 (2.4; 3.8)	4.3 (3.7; 5.0)
1998-2001	1980-85	4.8 (3.4; 6.3)	3.4 (2.3; 4.4)	4.1 (3.2; 4.9)

Table 5. Linear and quadratic term (best estimates and 95% confidence intervals) in eq. (4) for the thyroid cancer incidence in the period 1990 – 2001 and the birth-year cohort 1968-85 in 684 Ukrainian and 458 Belarusian settlements.

Area/dosimetry	β_1 (10^4 PY Gy)$^{-1}$			β_2 (10^4 PY Gy^2)$^{-1}$		
	females	males	both	females	males	both
Ukraine	2.2 (1.4; 3.1)	1.3 (0.7; 2.0)	1.6 (1.0; 2.2)	-0.18 (-0.24;-0.11)	0.08 (-0.19; 0.36)	0.02 (-0.19; 0.24)
Belarus/GSF	4.3 (3.5; 5.1)	3.3 (2.9; 3.8)	3.7 (3.3; 4.2)	-0.31 (-0.37;-0.25)	-0.20 (-0.23;-0.17)	-0.23 (-0.26;-0.20)
Belarus/FENIX	3.8 (3.0; 4.6)	3.0 (2.5; 3.6)	3.4 (3.0; 3.9)	-0.19 (-0.38;-0.01)	-0.17 (-0.19;-0.14)	-0.19 (-0.21;-0.16)
Both countries/GSF	3.5 (2.9; 4.1)	2.5 (2.0; 3.0)	2.9 (2.5; 3.3)	-0.25 (-0.29;-0.21)	-0.07 (-0.22; 0.08)	-0.14 (-0.26;-0.03)
Both countries/FENIX	3.2 (2.6; 3.8)	2.5 (2.0; 2.9)	2.8 (2.4; 3.1)	-0.15 (-0.31; 0.00)	-0.11 (-0.20;-0.02)	-0.13 (-0.21;-0.05)

Table 6. ERR per dose (best estimates and 95% confidence intervals) for the thyroid cancer incidence in 684 Ukrainian and 458 Belarusian settlements, based on the FENIX estimates of thyroid doses.

Period of operation year	Birth-year cohort	Excess relative risk per dose (Gy^{-1})		
		females	males	both
1990-93	1968-85	12 (4; 19)	39 (-16; 93)	16 (7; 25)
1994-97		8.5 (4.6; 12.3)	157 (-365; 679)	14 (8; 19)
1998-2001		4.6 (2.8; 6.4)	21 (7; 36)	7.0 (4.9; 9.2)
1990-2001	1968-73	3.2 (0.9; 5.5)	8.5 (0.4; 17)	3.4 (1.4; 5.5)
	1974-79	5.9 (2.5; 9.4)	59 (-32; 150)	12 (6; 17)
	1980-85	30 (2; 58)	-	51 (-5; 107)



Minsk
Mogilev
3 ... 10
1 ... 3
0.3 ... 1
0.1 ... 0.3
0.03 ... 0.1
0.01 ... 0.03
Russia
Gomel
Belarus
Chernigov
Ukraine
Kiev
Zhytomir
200
100
0
−100
Y, km
−150
−100
−50
0
50
100
X, km

Figure 1.

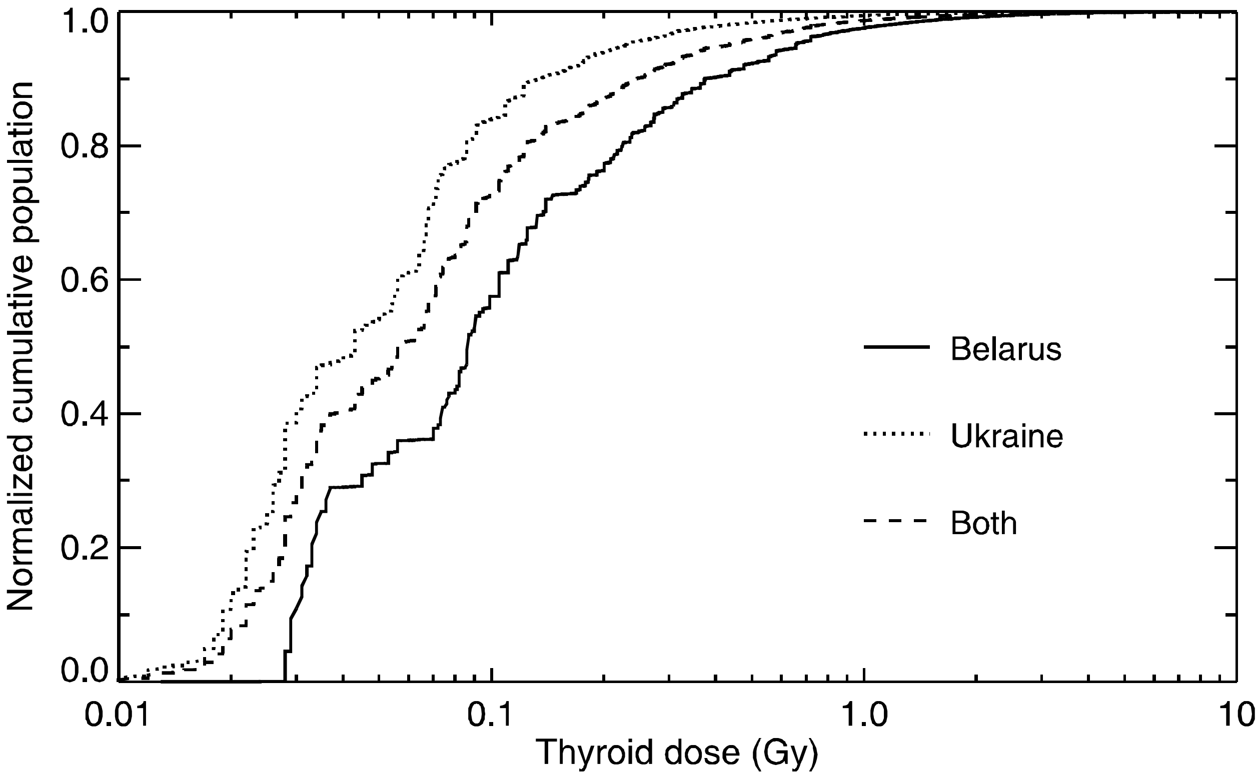

1.0
0.8
0.6
0.4
0.2
0.0
Normalized cumulative population
0.01
0.1
1.0
10
Thyroid dose (Gy)
Belarus
Ukraine
Both

Figure 2.

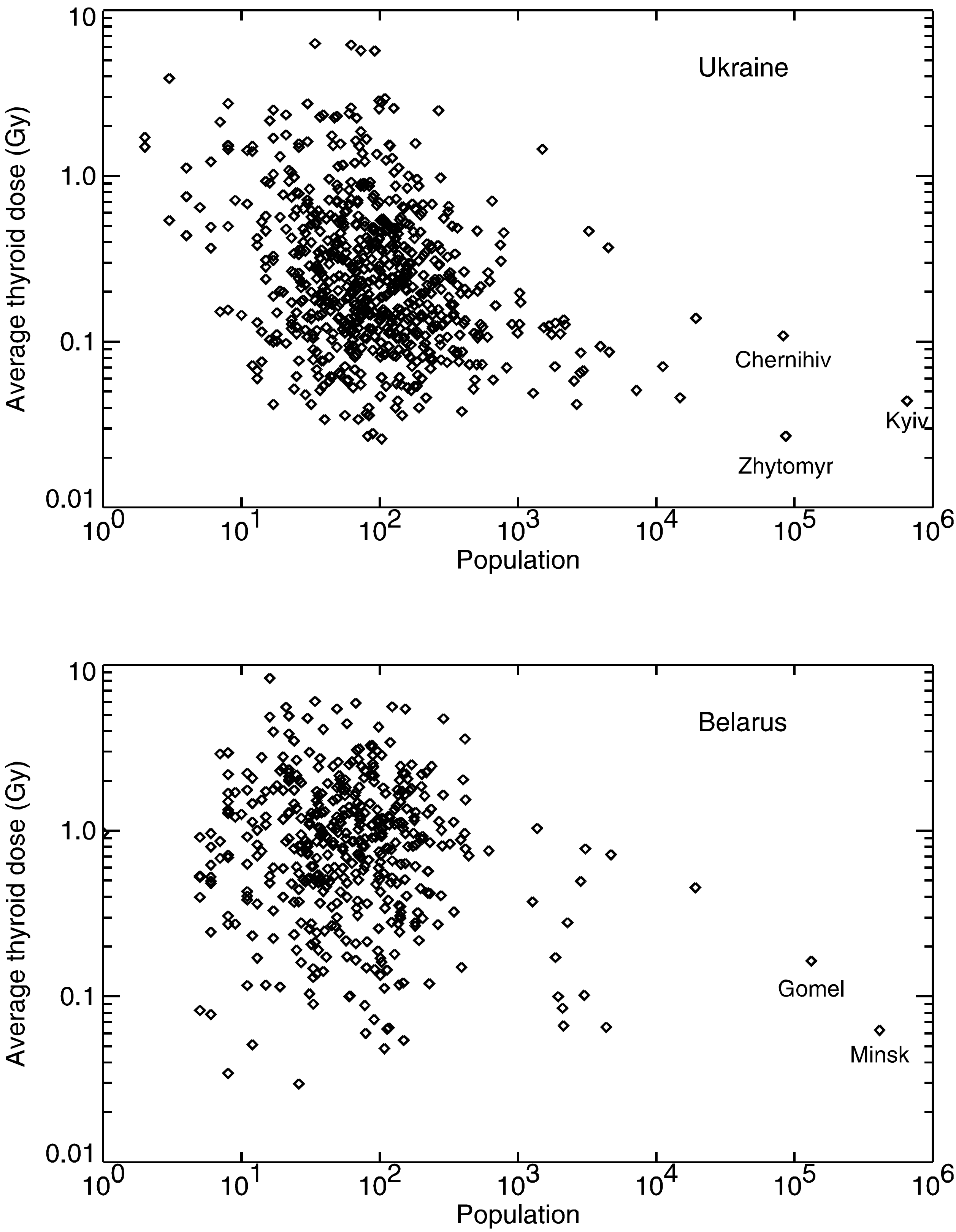

Ukraine
Chernihiv
Kyiv
Zhytomyr
Average thyroid dose (Gy)
Population
10
1.0
0.1
0.01
10^0 10^1 10^2 10^3 10^4 10^5 10^6
Belarus
Gomel
Minsk
Average thyroid dose (Gy)
Population
10
1.0
0.1
0.01
10^0 10^1 10^2 10^3 10^4 10^5 10^6

Figure 3.

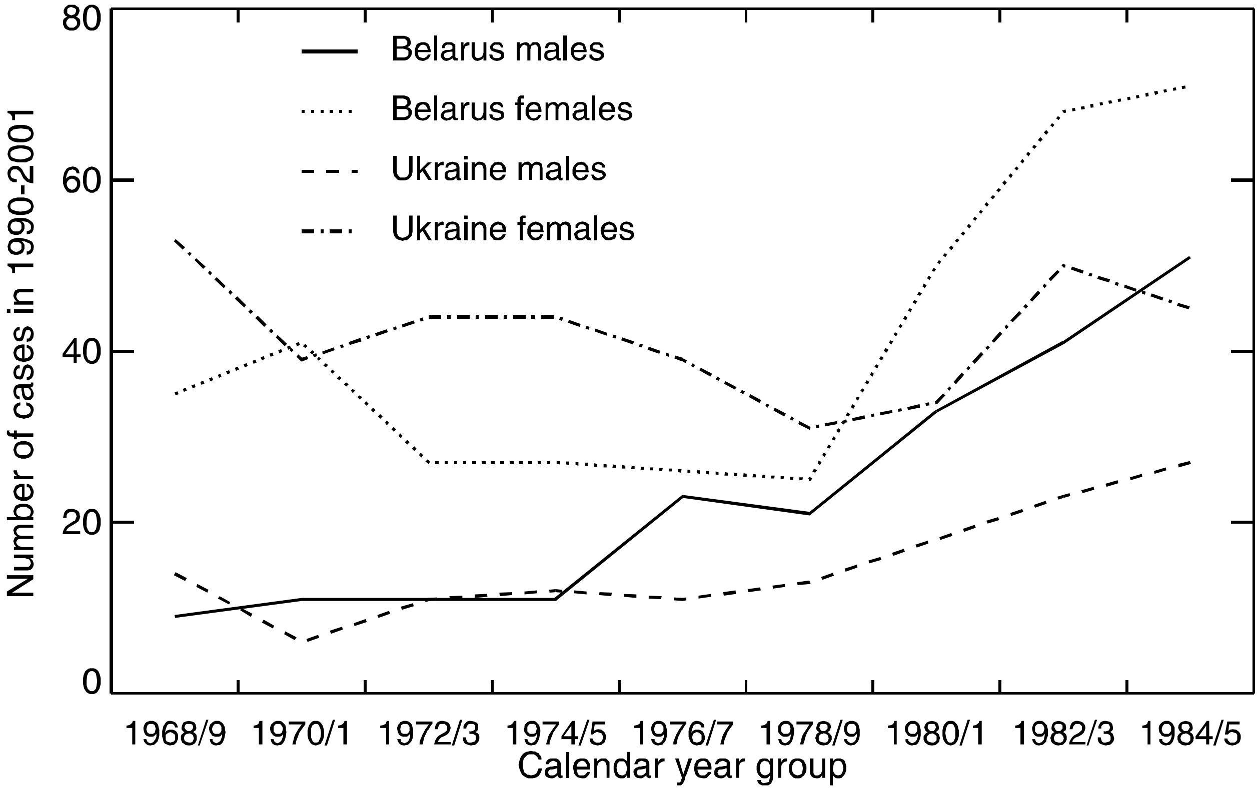

80
60
40
20
0
Number of cases in 1990-2001
Belarus males
Belarus females
Ukraine males
Ukraine females
1968/9
1970/1
1972/3
1974/5
1976/7
1978/9
1980/1
1982/3
1984/5
Calendar year group

Figure 4.

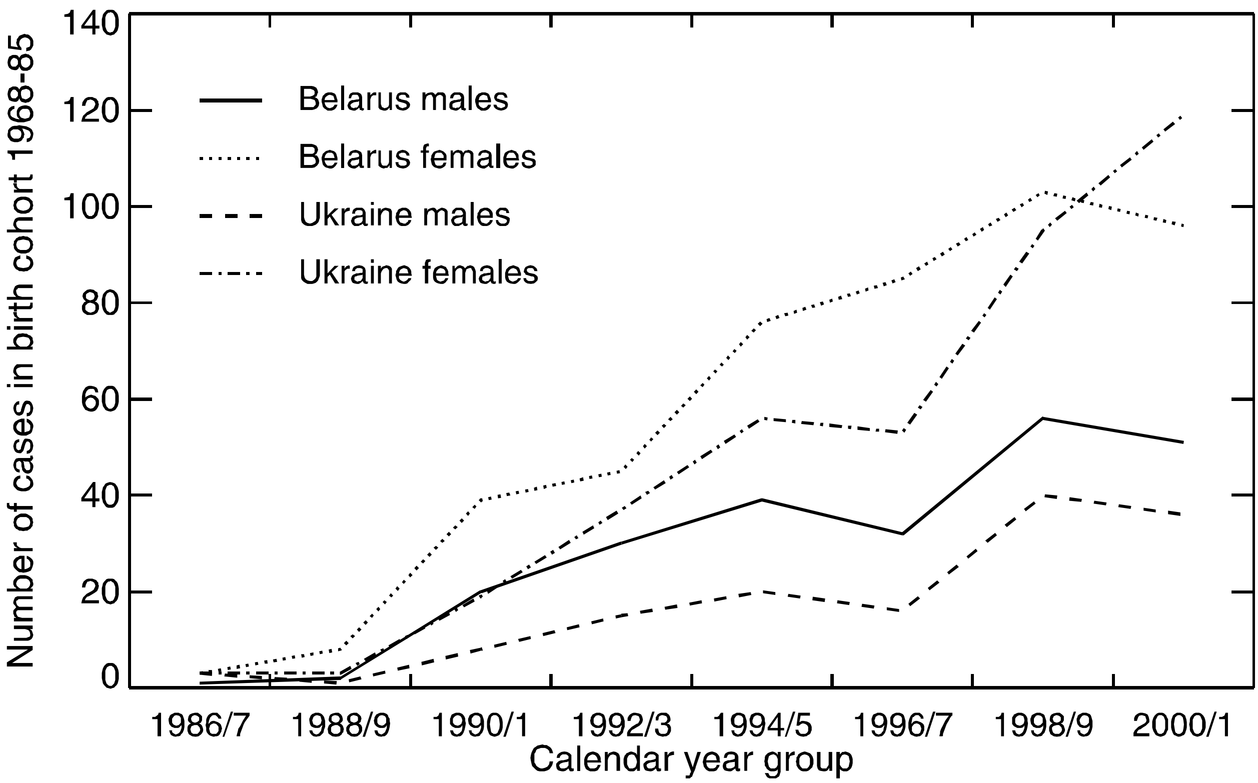

Number of cases in birth cohort 1968-85
140
120
100
80
60
40
20
0
Belarus males
Belarus females
Ukraine males
Ukraine females
1986/7
1988/9
1990/1
1992/3
1994/5
1996/7
1998/9
2000/1
Calendar year group

Figure 5.