ASSESSMENT OF CHERNOBYL MALIGNANT NEOPLASMS IN EUROPEAN COUNTRIES

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Abstract. The present report estimates the expected increase in the incidence and mortality from malignant neoplasms in 1986-2056 in European countries resulting from the accident at the Chernobyl nuclear power plant in 1986. The estimation of the number of excess incident cancers is based on the absolute excess radiation risk determined for the population of Belarus. For all European countries combined, 92,600 excess thyroid cancers (90% CI from 44,000 to 141,200 cases), 130,400 solid cancers other than thyroid and non-melanoma skin cancers (42,900 to 217,900), and 12,900 leukaemia cases (2,800 to 23,000) are predicted during 1986-2056. This corresponds to a time-averaged relative increase of *RR*=1.050 for thyroid cancers (90% CI from 1.024 to 1.077), *RR*=1.001 for solid cancers other than thyroid and non-melanoma skin cancers (1.000 to 1.002), and *RR*=1.003 for leukaemia (1.001 to 1.005).

Approximately two thirds of all additional cancers will occur in Belarus, Ukraine, and Russia. Belarus will account for about 20% of all additional solid cancer and leukaemia cases. In Belarus alone, approximately 31,400 additional incident thyroid cancers (15,400 to 47,400), 28,300 solid cancers other than thyroid and non-melanoma skin cancers (11,800 to 44,800), and approximately 2,800 additional leukaemia cases (1,000 to 4,600) are expected. The corresponding time-averaged relative risks are *RR*=2.625 for thyroid cancers (90% CI from 1.797 to 3.460), *RR*=1.012 for solid cancers other than thyroid and non-melanoma skin cancers (90% CI from 1.008 to 1.016), and *RR*=1.047 for leukaemia (1.017 to 1.077).
The predicted numbers of excess fatal cancers in Europe, 1986-2056, are as follows: 26,300 thyroid cancers (90%CI from 12,500 to 40,100), 81,300 solid cancers other than thyroid and non-melanoma skin cancers (90%CI from 23,000 to 139,600), and 9,100 leukaemia cases (90%CI from 1,500 to 16,700). Again, approximately two thirds of the additional fatal cancers will occur in Belarus, Ukraine and the Russian Federation.

Introduction.

The Chernobyl accident caused radioactive contamination of many countries of the Northern Hemisphere including the USA, Japan, China, and India [1,2]. Millions of people were exposed to radiation from the Chernobyl fallout. According to the present knowledge there is no threshold for the carcinogenic effect of ionising radiation [3]. Therefore any additional irradiation will induce additional cancers and leukaemia cases in irradiated populations, not only in the most contaminated regions of the former Soviet Union but all around Europe and in other countries. The first prognosis of the possible number of excess cancer cases in the Northern Hemisphere was already performed some months after the Chernobyl accident by Gofman [4]. It yielded 475,000 additional fatal solid cancers and 19,500 leukaemia cases for an infinite time period. A later study [5] yielded 17,400 fatal cancer and leukaemia cases within 50 years following the accident. Also subsequent studies [6-10] show large differences in the estimated numbers of excess cancers [9,10].

The objective of this study is to analyse the reasons for the disagreements in the existing estimates and to present a more reliable prognosis based on the effects observed in Belarus. The reason for choosing Belarus as a reference country is that Belarus is the country with the highest average fallout from Chernobyl, and that Belarus, other than Ukraine and Russia, has a cancer register which was already established long before 1986.

Materials and methods

Data on the caesium ground deposition after Chernobyl in different countries of the Northern Hemisphere, the respective radiation doses, and other relevant information [1,2], was used to forecast the numbers of expected excess cancer and leukaemia cases.
The estimation of radiation-induced malignant neoplasms was carried out for 1986-2056, using an approach developed by Malko [9,10]. This method relies on a transfer of the absolute radiation risks as determined for the Belarusian population within a certain time span T on other affected populations in Europe. The number n_i^T of excess cancers of the *i-th* site equals the corresponding number of excess cases in Belarus times the ratio of collective doses in country X and in Belarus.

$$n_{i,X}^{T} \approx \frac{H_{i,X}^{T,coll}}{H_{i,B}^{T,coll}} \cdot n_{i,B}^{T} \qquad (1)$$

$H_{i,X}^{T,Coll}$ and $H_{i,B}^{T,Coll}$ are collective radiation doses of the population X and of the population of Belarus (B), respectively, and $n_{i,X}^{T}$ and $n_{i,B}^{T}$ are the corresponding numbers of additional cancer cases of the *i-th* site in these populations in time period T.

The collective dose is the average individual dose times the number of exposed individuals. Since the average of the caesium ground deposition in country X, multiplied by the number of inhabitants equals the total caesium deposition in country X times the average population density, equation 1 can be written in the following form.

$$n_{i,X}^{T} \approx \frac{\rho_X^T \cdot Q_X^0}{\rho_B^T \cdot Q_B^0} \cdot n_{i,B}^{T}. \qquad (2)$$

Here ρ_X^T and ρ_B^T are the population densities in country X and Belarus, respectively, and Q_X^0 and Q_B^0 refer to the corresponding total caesium ground deposition in country X and Belarus.

Choosing Belarus as the reference country for determining the numbers of expected radiation-induced malignant neoplasms in the affected countries of Europe has two reasons. Firstly, Belarus was affected by the Chernobyl accident more than any other country of the world. According to [1], the caesium-137 ground deposition did not exceed 185 kBq/m^2 (5 Ci/km^2) outside the former Soviet Union. In Belarus, the caesium-137 ground deposition reached 59,200 kBq/m^2 (1,600 Ci/km^2) [11]. This is about 300-times the maximum contamination beyond the former Soviet Union. In extreme cases, individual whole body doses reached 1,500 mSv [12]. In Belarus, doses to the thyroid gland were much higher than whole body doses; in some cases they exceeded 60 Gy [13]. In no other country there is a greater chance of finding evidence of possible adverse health effects from Chernobyl than in Belarus. Secondly, Belarus has a cancer registry which was already established in 1953 [14] and since 1973 all data exist in computerized form.

The above approach has some advantages to the conventional method based on radiation risks derived from the Japanese atomic bomb survivors. While the doses to the survivors of Hiroshima and Nagasaki were delivered within approximately 1 microsecond, the radiation exposure to the thyroid, mainly from iodine-131, lasted several weeks and the exposure from caesium-137 many years. Also, the Japanese atomic bomb survivors were exposed to external high energy gamma radiation while the main radiation dose from Chernobyl was attributable to incorporated radionuclides with much smaller gamma energies. A substantial part of the radiation burden from Chernobyl came from incorporated α and β emitters. For these reasons it is problematic to apply the risk factors determined for the Japanese atomic bomb survivors to populations affected by the Chernobyl fallout.

The method of risk transfer described above depends upon the knowledge of the average caesium ground deposition and on the precision of the assessment of the number of excess cancers in Belarus. Implicitly we assume - based on a linear dose response model - that the absolute radiation risk factor in country X is the same as in Belarus. This is probably not true, since in most countries of Western Europe the life expectancy is longer than in Belarus and, consequently, the spontaneous cancer rates are considerably higher. Therefore the method will tend to underestimate the real number of excess cases.

Results

Thyroid doses

At present there is only one literature source containing data on thyroid doses in European countries affected by the Chernobyl fallout, the UNSCEAR 1988 Report [1]. This report provides mean thyroid doses for infants and adults. They were determined from measurements of the concentration of ^{131}I in food from April 26, 1986 to 30 April 30, 1987. Contributions of other pathways such as inhalation or external irradiation of the thyroid gland, and doses from other radionuclides were also taken into account. The dose estimates were based on values of the iodine-131 concentration in food and average consumption rates supplied by national organisations.

A comparison of the UNSCEAR estimates of thyroid doses with calculations conducted in many affected countries shows quite good agreement for most countries except for Belarus, Russia, and Ukraine.

Mean thyroid doses and other related values for infants and adults in Belarus (Region 1 of the former Soviet Union), in highly contaminated areas of Ukraine (Region 2) and less contaminated areas of Ukraine (Region 3), and in Russia (Region 4) were also estimated in [1]. For Belarus, however, the UNSCEAR data show considerable inconsistencies; we therefore did not to use them in our own approach. Instead we based our calculation on observed numbers of thyroid cancers in children.

Thyroid cancer in children is a very rare disease. According to Demidchik et al. [17], during 1966-1985, only 21 cases of thyroid cancer were registered among Belarusian children younger than 15 years at the time of diagnosis. This is about one case per year. Dividing the observed 21 thyroid cancers in children by the number of person-years (PY) in 1966-1985 ($4.74 \cdot 10^7$ PY, see [18,19]) yields an incidence rate of 0.443 cases per million PY. Table 1 shows that this value agrees well with the incidence rates of thyroid cancer in children of other European countries.

Table 1. Time-averaged crude and standardised (World standard) rates of the incidence of thyroid cancers in children.

Country	Time Period	Crude rate, 10^6 a^{-1}	Standardized rate, 10^6 a^{-1}	Sources
UK, England and Wales	1981-1990	0.6	0.5	[20]
UK, England and Scottish Cancer Register	1981-1990	0.6	0.5	[20]
Poland	1980-1989	0.5	0.5	[20]
Slovakia	1980-1989	0.7	0.6	[20]
Hungary	1985-1990	0.3	0.3	[20]
Ukraine	before Chernobyl	0.5	-	[21]
Belarus	1966-1985	0.44	-	this report

For the following estimation of the number of excess thyroid cases in Belarus after Chernobyl we define the spontaneous rate of 0.433 cases per million, determined before Chernobyl, as expected rate in the years after 1986.

Tronko et al. [21] reported that 572 cases of thyroid cancers were registered in Ukrainian children (younger than 15 years at diagnosis) in 1986-2000. The spontaneous incidence rate of thyroid cancers in children of Ukraine before the Chernobyl accident was approximately 0.5 cases per million person-years [21] (see Table 1), nearly the same as in Belarus. The number of children in Ukraine is about 5-times greater than in Belarus [23], i.e., we expect about 5 spontaneous thyroid cancer cases per year in Ukrainian children. During 1986-2000, we then obtain a number of 497 excess thyroid cancers (572 minus 75) in Ukrainian children.
The number of excess thyroid cancers among Belarusian children (663 cases) is 1.33-times greater than the number of excess thyroid cancers (497 cases) in children of Ukraine until 2000. We therefore conclude that the collective thyroid dose of children in Belarus was 1.33-times greater than in Ukraine. In the Russian Federation, the number of thyroid cancers in children is smaller than in Ukraine [24-26].

Recently Likhtarev et al. [27] published thyroid doses from ^{131}I for all regions of Ukraine including Kiev City. These data were estimated for children and adolescents (0-18 years) at the time of the Chernobyl accident. The collective thyroid dose was estimated as 300,000 PGy based on the regional average individual thyroid doses [27] and the population numbers in the Ukrainian regions given in [23]. In Belarus, children and adolescents received 42% of the collective thyroid dose [28]. Under the assumption that this proportion is also true for Ukraine, a total collective thyroid dose of 705,000 PGy (300,000 divided by 0,42) is estimated. This number, multiplied by the factor of 1.33 derived above, gives 940,000 PGy which we consider the “true” collective thyroid dose of the Belarusian population. It is approximately 70% greater than the collective dose reported in [28-30].

It seems to us that, at present, 940,000 PGy is the best estimate of the collective thyroid dose of the Belarusian population. This follows from a study which shows that the collective thyroid dose reported in [28-30] is underestimated because the thyroid doses of the Belarusian population during the first 10 days after the Chernobyl accident were not determined correctly [31].

A collective thyroid dose of 553,000 PGy [30] was used in [9,10] to predict the number of additional thyroid cancers in Belarus and other countries. This value was chosen because it allows a better description of the temporal trend of the collective thyroid dose delivered to the Belarusian population as a result of the Chernobyl accident. In [30] the thyroid doses in Belarus were estimated for 3 subgroups: for children, for adolescents, and for adults. This way the collective dose can be determined more precisely than in [28,29] where only two subgroups - children and adults - were considered. Based on a collective dose of 553,000 PGy, an excessive absolute risk (EAR) of radiation-induced thyroid cancers of 16.65 cases per 10,000 PYGy is obtained [9,10]. The collective dose of 940,000 PGy, determined above, corresponds to 9.8 cases per 10,000 PYGy, which still is 6-times greater than the EAR of 1.6 cases per 10,000 PYGy determined for atomic bomb survivors [32].

Prediction of additional malignant neoplasms.

Thyroid cancers

Equation (1) was used in the present report for the assessment of the number of radiation-induced thyroid cancers expected in European countries in 1986-2056 as a result of the Chernobyl accident. The number of excess solid cancers other than thyroid cancers and non-melanoma skin cancers, and the numbers of additional leukaemia cases, were estimated on the basis of equation (2).

The numbers of cancers in Belarus expected during 1986-2056 that were used to determine the numbers of excess cases in other countries are given in reports [9,10]. They are: 31,400 excess thyroid cancers, 28,300 solid cancers other than thyroid and non-melanoma skin cancers, and 2,800 leukaemia cases. According to [9,10] the accuracy of estimations of additional thyroid cancers, solid cancers other than non-melanoma skin cancers as well as additional leukaemia cases might be approximately 50%. And this uncertainty was included in the assessment of confidence carried out in the present report. 90% Confidence intervals of the relative risks were calculated on the basis of the Poisson distribution.

The relative risk is the ratio of the number of expected plus excess cancers to the number of expected cancers.

$$RR_X^T = \frac{n_X^T + n_{X,Sp}^T}{n_{x,Sp}^T}$$

Here RR_X^T is the time-averaged relative cancer risk in population *X*, n_X^T is the number of excess additional cancers and $n_{X,Sp}^T$ the number of expected cancers in time *T*.

The number of spontaneous cancers was calculated with the incidence rate of cancers in 2002 [33]. This assumption inevitably causes some errors in the estimation of relative risks but they are insignificant compared to other errors.

Because of uncertainties of the collective thyroid dose of the Belarusian population described in the previous section, the assessment of the number of radiation-induced thyroid cancers in the affected countries of Europe was carried out using two collective thyroid doses for Belarus, 940,000 PGy and 553,000 PGy [30]. Data estimated on the basis of 940,000 PGy are presented in Table 2 (Low Estimate). Data assessed on the basis of 553,000 PGy are given in Table 3 (High Estimate). The tables have a similar structure. The first column shows the country, the second and third column contain the numbers of excess cancers and of expected cancers, respectively. The fourth column gives the sums of observed (= excess plus spontaneous) cancers, and the fifth column shows the relative risks, i.e. observed divided by expected cancers. The sixth column, eventually, contains the 90% confidence interval (CI) of the relative risk

A special procedure was adopted for the assessment of radiation-induced thyroid cancers in the Russian Federation and Ukraine. To calculate the expected number of excess thyroid cancers in Ukraine, 1986-2056, the number of excess thyroid cancers in Belarus [9,10] was divided by 1.334, the ratio of excess thyroid cancers in children from Belarus, 1990-2000, to the number of excess thyroid cancers in children from Ukraine, 1986-2000. The number of additional thyroid cancers for Russia was also estimated on the basis of registered thyroid cancers in children from Russia [24-26] and children from Belarus. This method to estimate the numbers of additional thyroid cancers for Ukraine and Russia is the reason why Tables 2 and 3 contain the same numbers of cases for these countries.

Table 2. Incidence of thyroid cancers, 1986-2056, in European countries affected by the Chernobyl accident (“Low Estimate”).

Country	Additional	Expected cases	Observed cases	RR	90% CI of RR
Austria	477	28,980	29,457	1.016	0.999÷1.034
Belarus	31,400	19,320	50,720	2.625	1.797÷3.460
Belgium	141	17,780	17,921	1.008	0.992÷1.024
Bulgaria	952	9,870	10,822	1.096	1.031÷1.162
Czechoslovakia	1,381	44,800	46,181	1.031	1.008÷1.054
Denmark	11	10,080	10,091	1.001	0.984÷1.018
Finland	197	21,140	21,337	1.009	0.993÷1.025
France	678	254,940	255,618	1.003	0.998÷1.007
Germany	1,479	188,300	189,779	1.004	1.000÷1.016
Greece	1,694	25,550	27,244	1.066	1.023÷1.110
Hungary	159	30,380	30,539	1.005	0.993÷1.017
Ireland	59	4,550	4,609	1.013	0.982÷1.044
Italy	3,037	227,780	230,817	1.013	1.003÷1.023
Luxemburg	8	918	926	1.009	0.950÷1.068
The Netherlands	193	24,570	24,763	1.008	0.993÷1.022
Norway	80	11,830	11,910	1.007	0.988÷1.025
Poland	1,895	105,560	107,455	1.018	1.004÷1.032
Portugal	1	37,310	37,311	1.000	0.991÷1.009
Romania	2,339	46,690	49,029	1.050	1.017÷1.083
Russia	10,828	368,480	379,308	1.029	1.012÷1.047
Spain	31	108,080	108,111	1.000	0.995÷1.005
Sweden	97	19,880	19,977	1.005	0.991÷1.019
Switzerland	528	23,660	24,188	1.022	1.000÷1.044
Ukraine	23,550	47,250	70,800	1.498	1.241÷1.758
United Kingdom	246	94,990	95,236	1.003	0.996÷1.009
Yugoslavia	4,199	61,660	65,859	1.068	1.027÷1.109
Belarus	31,400	19,320	50,720	2.625	1.797÷3.460
Belarus, Russia and Ukraine	65,778	435,050	500,828	1.151	1.073÷1.230
Other countries	19,882	1,399,298	1,419,180	1.014	1.006÷1.023
All countries	85,660	1,834,348	1,920,008	1.047	1.022÷1.071

The assessment of additional thyroid cancers in countries other than Belarus, Russia and Ukraine was performed using data given in the UNSCEAR report from 1988 [1] which still contained data for Czechoslovakia and Yugoslavia. Since there are no new data for these territories, Table 2 contains estimates for theses former states.

As can be seen from Table 2 (Low Estimate) using the value 940,000 PGy as collective thyroid dose for the Belarusian population gives approximately 86,000 additional thyroid cancers that can be expected in Europe in 1986-2056. About 77% of all excess thyroid cancers are expected to occur in Belarus, Ukraine, and Russia/

With a collective thyroid dose of 553,000 PGy the total number of excess thyroid cancers increases to approximately 100,000 cases. The contribution of Belarus, Ukraine and Russia will be about 63% (see Table 3 (High Estimate)).

Table 3. Incidence of thyroid cancers in 1986-2056 in European countries affected by the Chernobyl accident ("High Estimate").

Country	Excess cases	Expected cases	Total	RR	90% CI
Austria	812	28,980	29,792	1.028	1.004 ÷ 1.052
Belarus	31,400	19,320	50,720	2.625	1.797 ÷ 3.460
Belgium	239	17,780	18,019	1.013	0.994 ÷ 1.033
Bulgaria	1,619	9,870	11,489	1.164	1.065 ÷ 1.265
Czechoslovakia	2,347	44,800	47,147	1.052	1.018 ÷ 1.087
Denmark	19	10,080	10,099	1.002	0.985 ÷ 1.018
Finland	334	21,140	21,474	1.005	0.997 ÷ 1.035
France	1,153	254,940	256,093	1.005	0.999 ÷ 1.010
Germany	2,514	188,300	190,814	1.014	1.003 ÷ 1.024
Greece	2,879	25,550	28,429	1.113	1.046 ÷ 1.180
Hungary	270	30,380	30,650	1.009	0.995 ÷ 1.023
Ireland	100	4,550	4,650	1.022	0.987 ÷ 1.058
Italy	5,162	227,780	232,942	1.023	1.008 ÷ 1.037
Luxemburg	13	910	923	1.014	0.952 ÷ 1.077
The Netherlands	328	24,570	24,898	1.013	0.996 ÷ 1.031
Norway	136	11,830	11,966	1.011	0.991 ÷ 1.032
Poland	3,221	105,560	108,781	1.031	1.010 ÷ 1.051
Portugal	2	37,310	37,312	1.000	0.992 ÷ 1.009
Romania	3,976	46,690	50,666	1.085	1.035 ÷ 1.136
Russia	10,828	368,480	379,308	1.029	1.012 ÷ 1.047
Spain	54	108,080	108,134	1.001	0.995 ÷ 1.006
Sweden	165	19,880	20,045	1.008	0.992 ÷ 1.024
Switzerland	898	23,660	24,558	1.038	1.008 ÷ 1.068
Ukraine	23,550	47,250	70,800	1.498	1.241 ÷ 1.758
United Kingdom	418	94,990	95,408	1.004	0.997 ÷ 1.012
Yugoslavia	7,137	61,660	68,797	1.116	1.051 ÷ 1.181
Belarus	31,400	19,320	50,720	2.625	1.797 ÷ 3.460
Belarus, Russia and Ukraine	65,778	435,050	500,828	1.151	1.073 ÷ 1.230
Other countries	33,796	1,399,290	1,433,086	1.024	1.011 ÷ 1.038
All countries	99,574	1,834,340	1,933,914	1.054	1.026 ÷ 1.083

The data in Tables 2 and 3 demonstrate that the highest increase in the incidence of thyroid cancers as a result of the Chernobyl accident will occur in Belarus. The time-averaged relative risk of thyroid cancers in Belarus in the period 1986-2056 is 2.625 (90%CI from 2.598 to 3.625). This corresponds to an attributable risk of 61.8% (90% CI from 44% to 71%). This indicates that at least 44%of all thyroid cancers registered in 1986-2056 in Belarus are radiation induced. The results are consistent with observed incidences of thyroid cancers in affected countries of Europe after the accident. In 2002, the registered incidence of thyroid cancers in Belarus was the highest in Europe while, before the Chernobyl accident, it was one of the lowest [33, 34].

A sharp increase in thyroid cancers was also observed in Ukraine. According to our assessment, the time-averaged relative risk of thyroid cancers is expected to be 1.498 (90% CI from 1.241 to 1.758) which corresponds to an attributive risk of 33.3% (90% CI from 16.1 to 50.6%), i.e., every third thyroid cancer will have been caused by the Chernobyl accident.
The predicted time-averaged relative risk of thyroid cancers in the Russian Federation, 1986-2056, is much lower than the respective values assessed for Belarus and Ukraine. It is only 1.029 (90% CI from 1.012 to 1.047). The reason is that any excess thyroid cancers are expected essentially in contaminated areas of the European part of Russia while the reference is the whole population of Russia.

There is no doubt that the observation of the incidence of thyroid cancers in contaminated areas of Ukraine and Russia will add to the evidence presented in the present report. The highest increase in thyroid cancers as a result of the Chernobyl accident outside of the former Soviet Union will appear in South and Central Europe, e.g. Bulgaria, Yugoslavia, Greece and Romania. The share of additional thyroid cancers in these countries during 1986-2056 might become 10% or more of all thyroid cancers (Table 3). The excess might well be large enough to reach statistical significance. In most European countries, however, the increase will be too small to be detectable by epidemiological studies.

The higher additional incidence of thyroid cancers in some countries of the South and Central Europe reflects higher thyroid doses of populations of these countries. The reason is that at the time of the Chernobyl accident the vegetation was more advanced due to the milder climate than in other affected European countries. This resulted in a higher consumption of leafy vegetables and milk contaminated with radioactive iodine in countries of South Europe and some countries of Central Europe and, consequently, in higher thyroid doses [1].

Other cancers

Table 4 shows the calculated numbers of additional solid cancers other than thyroid cancers and non-melanoma skin cancers expected in the affected countries as a result of the Chernobyl accident. They were calculated using expression (2).
Table 5 presents the number of additional leukaemia cases in affected countries of Europe including Belarus, Russia and Ukraine. They were also calculated on the basis of expression (2).

Data of the average caesium-137 ground deposition in each country given in [2] and data of population numbers provided in [1] were used to estimate the numbers of additional solid cancers and leukaemia cases which are presented in Tables 4 and 5.

Table 4. Incidence of solid cancers other than thyroid and non-melanoma skin cancers in 1986-2056 in European countries affected by the Chernobyl accident.

Country	Additional	Spontaneous	Total	RR	90%CI of RR

Austria	5,050	2,463,300	2,468,350	1.002	1.000 ÷1.004
Belarus	28,300	1,948,730	1,977,030	1.015	1.008 ÷1.023
Belgium	110	3,516,660	3,516,770	1.000	0.999 ÷1.001
Bulgaria	2,920	1,607,130	1,610,050	1.002	1.000 ÷1.004
Croatia	630	1,372,000	1,372,630	1.000	0.999 ÷1.002
Czech Republic	1,410	3,162,880	3,164,290	1.000	0.999 ÷1.002
Denmark	70	1,694,770	1,694,840	1.000	0.999 ÷1.001
Estonia	60	350,700	350,760	1.000	0.997 ÷1.003
Finland	1,600	1,426,600	1,428,200	1.001	0.999 ÷1.003
France	1,220	17,999,310	18,000,530	1.000	1.000 ÷1.001
Germany	9,280	27,623,470	27,632,750	1.000	1.000 ÷1.001
Greece	1,880	2,595,880	2,597,760	1.001	0.999 ÷1.002
Hungary	625	3,329,130	3,329,755	1.000	0.999 ÷1.001
Ireland	375	890,330	890,705	1.000	0.998 ÷1.002
Italy	3,770	19,646,200	19,649,970	1.000	1.000 ÷1.001
Latvia	75	509,040	509,115	1.000	0.998 ÷1.003
Lithuania	420	780,920	781,340	1.001	0.998 ÷1.003
Luxemburg	15	138,390	138,405	1.000	0.996 ÷1.005
Moldavia	1,320	635,320	636,640	1.002	0.999 ÷1.005
The Netherlands	135	4,742,850	4,742,985	1.000	0.999 ÷1.001
Norway	920	1,411,760	1,412,680	1.001	0.999 ÷1.002
Poland	1,755	9,113,510	9,115,265	1.000	1.000 ÷1.001
Romania	5,220	4,053,070	4,058,290	1.001	1.000 ÷1.003
Russia	25,400	25,998,910	26,024,310	1.001	1.000 ÷1.002
Slovakia	715	1,265,880	1,266,595	1.001	0.999 ÷1.002
Slovenia	960	523,040	524,000	1.002	0.999 ÷1.005
Spain	80	10,908,940	10,909,020	1.000	1.000 ÷1.001
Sweden	1,980	2,894,920	2,896,900	1.001	0.999 ÷1.002
Switzerland	1,530	2,398,970	2,400,500	1.001	0.999 ÷1.002
Ukraine	28,300	9,653,210	9,681,510	1.003	1.002 ÷1.005
UK	4,280	18,777,220	18,781,500	1.000	1.000 ÷1.001
Belarus	28,300	1,948,730	1,977,030	1.015	1.008 ÷1.023
Belarus, Russia and Ukraine	82,000	37,600,850	37,682,850	1.002	1.001 ÷1.004
Other countries	48,405	145,832,190	145,880,595	1.000	1.000 ÷1.001
All countries	130,405	183,433,040	183,563,445	1.001	1.000 ÷1.001

As can be seen from Tables 4 and 5, the calculated excess of solid cancers other than thyroid and non-melanoma skin cancers, as well as of leukaemia, is not significant in the countries outside the former Soviet Union. The highest relative increase is found in Belarus. This is also true for leukaemia. In Belarus, the relative risk of solid cancers other than thyroid and non-melanoma skin cancers in 1986-2056 is RR=1.015 (90% CI from 1.008 to 1.023) (see Table 4) and for leukaemia RR=1.047 (90%CI from 1.017 to 1.078) (see Table 5).

Table 5. Incidence of leukaemia in 1986-2056 in European countries affected by the Chernobyl accident.

Country	Additional	Spontaneous	Total	RR	90% CI
Austria	500	63,910	64,410	1.008	0.998 ÷ 1.018
Belarus	2,800	59,220	62,020	1.047	1.017 ÷ 1.078
Belgium	11	96,740	96,751	1.000	0.995 ÷ 1.005
Bulgaria	289	35,700	35,989	1.008	0.995 ÷ 1.021
Croatia	62	43,190	43,252	1.001	0.994 ÷ 1.010

Czechoslovakia	140	77,350	77,490	1.002	0.995 ÷ 1.009
Denmark	7	53,830	53,837	1.000	0.993 ÷ 1.007
Estonia	6	9,310	9,316	1.001	0.983 ÷ 1.018
Finland	158	27,720	27,878	1.006	0.993 ÷ 1.018
France	121	557,690	557,811	1.000	0.998 ÷ 1.003
Germany	918	742,070	742,988	1.001	0.999 ÷ 1.004
Greece	186	93,520	93,706	1.000	0.998 ÷ 1.008
Hungary	62	84,630	84,692	1.001	0.998 ÷ 1.007
Ireland	37	24,290	24,327	1.002	0.990 ÷ 1.013
Italy	373	566,230	566,603	1.001	0.998 ÷ 1.003
Latvia	7	21,980	21,987	1.000	0.989 ÷ 1.012
Lithuania	42	29,610	29,652	1.001	0.991 ÷ 1.012
Luxemburg	2	4,480	4,482	1.000	0.976 ÷ 1.025
Moldavia	131	16,380	16,511	1.003	0.991 ÷ 1.025
The Netherlands	13	100,800	100,813	1.000	0.995 ÷ 1.005
Norway	91	30,450	30,541	1.003	0.992 ÷ 1.014
Poland	174	200,760	200,934	1.000	0.998 ÷ 1.005
Romania	517	93,170	93,687	1.006	0.998 ÷ 1.014
Russia	2,512	759,290	761,802	1.003	1.000 ÷ 1.007
Slovakia	71	32,410	32,481	1.002	0.992 ÷ 1.012
Slovenia	95	12,810	12,905	1.007	0.989 ÷ 1.026
Spain	8	305,340	305,348	1.000	0.997 ÷ 1.003
Sweden	196	72,100	72,296	1.003	0.995 ÷ 1.010
Switzerland	151	58,450	58,601	1.003	0.994 ÷ 1.011
Ukraine	2,801	176,680	179,481	1.016	1.004 ÷ 1.028
United Kingdom	423	489,090	489,513	1.001	0.998 ÷ 1.004
Belarus	2,800	59,220	62,020	1.047	1.017 ÷ 1.078
Belarus, Russia and Ukraine	8,113	995,190	995,190	1.008	1.002 ÷ 1.014
Other countries	4,791	3,944,010	3,948,801	1.001	1.000 ÷ 1.003
All countries	12,904	4,939,200	4,952,104	1.003	1.001 ÷ 1.005

The values of relative risk of solid cancers other than thyroid and non-melanoma skin cancers that can be expected for Russia and Ukraine are much lower than for Belarus. Therefore it is unlikely that epidemiological studies will be able to detect any excess cancers in Russia and Ukraine, and it will be virtually impossible in other European countries.

Table 6 contains rounded values for excess cancers established in the present report for Belarus, for Russia and Ukraine, for all other European countries, and for all European countries including Belarus, Russia and Ukraine. The last column shows the share that the country holds of the excess cancers in all countries combined.

Table 6. Predicted numbers of excess cases, 1986-2056, in European countries after the Chernobyl accident.

Countries	Excess cases		Relative risk		Contribution
	Cases	90%CI	RR	90%CI of RR	%
Thyroid cancers					
Belarus	31,400	15,400÷47,500	2.625	1.797÷3.460	33.9
Belarus,	65,800	31,800÷99,900	1.151	1.073÷1.230	71.1

Russia and Ukraine					
Other countries	26,800	11,500÷42,200	1.019	1.008÷1.030	28.9
All countries	92,600	44,000÷141,200	1.050	1.024÷1.077	100
Solid cancers other than thyroid and non-melanoma skin cancers					
Belarus	28,300	11,800÷44,800	1.015	1.008÷1.023	21.7
Belarus, Russia and Ukraine	82,000	30,900÷133,100	1.002	1.001÷1.004	62.9
Other countries.	48,400	4,300÷92,500	1.000	1.000÷1.001	37.1
All countries	130,400	42,900÷217,900	1.001	1.000÷1.001	100
Leukaemia					
Belarus	2,800	1,000÷4,600	1.047	1.017÷1.078	21.7
Belarus, Russia and Ukraine	8,100	2,400÷13,800	1.008	1.002÷1.014	62.8
Other countries	4,800	-870÷10,470	1.001	1.000÷1.003	37.2
All countries	12,900	2,800÷23,000	1.003	1.001÷1.005	100

In all European countries combined, 92,600 additional thyroid cancers (90% CI from 44,000 to 141,200 cases), 130,400 additional solid cancers other than thyroid and non-melanoma skin cancers (90% CI from 42,900 to 217, 900 cases) and 12,900 additional leukaemia cases (90% CI from 2,800 to 23,000 cases) are expected in the affected countries as a result of the Chernobyl accident during 1986-2056. The number of additional thyroid cancers (92,600 cases) is the arithmetic mean of values given for all affected countries in Europe including Belarus, Russia and Ukraine in Tables 2 and 3. Approximately two thirds of all excess cancers will occur in Belarus, Ukraine and Russia. Belarus alone will contribute about 20% to all excess solid cancers and leukaemia cases.

Table 7 shows data on the excess mortality as a result of the Chernobyl accident in European countries including Belarus, Ukraine and Russia.

Table 7. Predicted mortality from malignant neoplasms in 1986-2065 in countries of Europe affected by the Chernobyl accident.

Countries	Additional mortality		Relative risk		Contribution
	Cases	90% CI	RR	90% CI of RR	%
Thyroid cancers					
Belarus	8,900	4,400÷13,500	2.625	1.797÷3.460	33.8

Belarus, Russia and Ukraine	18,700	9,000÷28,400	1.151	1.073÷1.230	71.1
Other countries	7,600	3,300÷12,100	1.019	1.008÷1.030	28.9
All countries	26,300	12,500÷40,100	1.050	1.024÷1.077	100
Solid cancers other than thyroid and non-melanoma skin cancers					
Belarus	17,600	7,000 ÷ 28,300	1.015	1.006÷1.023	21.6
Belarus, Russia and Ukraina	51,100	17,600 ÷ 84,600	1.002	1.001÷1.004	62.9
Other countries.	30,200	-600 ÷ 60,900	1.000	1.000÷1.001	37.1
All countries	81,300	23,000 ÷ 139,500	1.001	1.000÷1.001	100
Leukaemia					
Belarus	1,970	650 ÷ 3,300	1.047	1.015÷1.079	21.6
Belarus, Russia and Ukraina	5,720	1,480 ÷ 9,970	1.008	1.002÷1.014	62.9
Other countries	3,380	-1060 ÷ 7,810	1.001	1.000÷1.003	37.1
All countries	9,100	1,480 ÷ 16,700	1.003	1.000÷1.005	100

The mortality data given in Table 7 were estimated by multiplying the assessed numbers of additional malignant neoplasms with coefficients of mortality. Averaged population-weighted ratios of the mortality rates to incidence rates registered in European countries in 2002 [33] were used. They are 0.284 for thyroid cancers, 0.623 for solid cancers other than thyroid and non-melanoma skin cancers, and 0.705 for leukaemia. These averaged values were applied for all countries analysed in the present report including Belarus, Ukraine, and Russia. This causes some incorrectness especially for the countries of the former Soviet Union that in 2002 had higher ratios for solid cancers other than thyroid and non-melanoma skin cancers as well as for leukaemia. However, this error lies within the range of other errors, implicit in applying an ecological model as well as the assumption of a constant absolute radiation risk factor in all countries.
The qualitative character of estimations carried out in the present report justifies this assumption.

As can be seen from Table 7, approximately 23,700 additional fatal thyroid cancers (90% from 11,000 to 36,400 cases), approximately 81,300 solid cancers other than thyroid and non-melanoma skin cancers (23,000 to 139,500) and approximately 9,100 leukaemia cases (1,480 to 16,700) are expected in Europe during 1986-2056 as a result of the Chernobyl accident .

Again, approximately two thirds of the additional fatal cancers are expected in Belarus, Ukraine, and the Russian Federation.
The prognosis of fatal cancers given in Table 7 yields 114,100 excess cases in Europe during 1986-2056 as a result of the Chernobyl accident. This is approximately 12% more than the 93,000 excess cases predicted for Europe in the same time span [9,10]. The reason for the difference lies in the differences of dose assessment and other ratios of mortality to incidence.

Comparison of prognosis

Table 8 shows comparison of data estimated in the present report with data assessed in reports [4,5,7,8]. There is a significant disagreement between the results of this study and those of other authors [4,5,7,8].

Table 8. Comparison of prognoses of excess incidence and mortality rates for malignant neoplasms resulting from the Chernobyl accident

Thyroid cancers	Solid cancers excluding thyroid and non-melanoma skin cancers	Leukaemia cases	Combined cases	Time period	Sources
		Incident cases			
15,700 (3,400-72,000)	22,800 (10,200-51,100)	2,400 (700- 7,700)	40,900	1986-2065	[8]
92,600 (44,000-141,200)	130,400 (42,900-217,900)	12,900 (2,800-23,000)	226,900	1986-2056	This report
		Cancer deaths			
	475,000	19,500	494,500	Infinite time	[4]
	17,400			1986-2036	[5]
			30,000-60,000	Infinite time	[7]
	14,100 (6,200-32,100)	1,650 (500-5,400)	15,750	1986-2065	[8]
26,300 (12,500÷40,100)	81,300 (23,000 ÷ 139,500)	9,100 (1,480 ÷ 16,700)	116,700	1986-2056	This report

As can be seen from Table 8, the confidence intervals for the numbers of additional malignant neoplasms estimated in the present report overlap with those in [8].
The estimates of the numbers of excess cases in Table 8 differ considerably. For example, the number of additional thyroid cancers estimated in the present report (92,600 cases) is 5.9-times higher than estimated by Cardis et al.[8] (15,700 cases).The number of additional solid cancers other than thyroid and non-melanoma skin cancers estimated in the present report is 130,400 cases, nearly 6-times more than predicted by Cardis et al. [8] (22,800 cases). For leukaemia cases this ratio is 5.4.
The contrary is true for the estimates by Gofman [4]. His estimate for fatal solid cancers is 475,000 excess cases which is 5.8-times more than the number of solid cancers other than thyroid and non-melanoma skin cancers predicted in the present report. Interestingly, his number of fatal leukaemia cases (19,500) is much closer to the results of this report (9,100 cases).

In the following we will show that the differences in the numbers of additional cancers and leukaemia cases result from incorrect predictions by Cardis et al.[8] and Gofman [4]. This is rather evident for thyroid cancers. Cardis et al.[8] estimated the numbers of additional cancers and leukaemia cases for two time periods, 1986-2005 and 1986-2065. Their data were used in the present report for an assessment of additional cancers and leukaemia cases also for these periods of time. We will apply the following three methods to determine the number of excess cases.

First method

The numbers of additional thyroid cancers in Belarus in 1986-2005 and in 1986-2065 assessed when the first method is applied are presented in Tables 9 and 10, respectively. Table 9 shows the results of for 1986-2005.

The data in the first, second, third and fourth column of Table 9 were copied from [4]. The data in the sixth column of Table 9 were obtained from statistical handbooks [23]. The last column of Table 9 contains numbers of additional thyroid cancers in Belarus in 1986-2005 assessed in the present report. They were estimated using data given in the third and fourth column of Table 9.

Cardis et al. [8] grouped the whole population of Europe in 5 categories according to their radiation doses. According to Cardis et al. [8] the population of Vitebsk region of Belarus belongs to the second group. The thyroid dose of populations in this group is 7 mSv [8]. Vitebsk region had a population of 1.404 million in 1986 [23]. With the numbers given by Cardis et al. [8] one obtains only 1 excess thyroid cancer case in Vitebsk region, and only 165 excess cases in Belarus, 1986-2005.

Table 9. Numbers of excess thyroid cancer cases in all European countries and in Belarusduring 1986-2005 according to Cardis et al. [8]

Group	All countries of Europe [8]			Regions of Belarus		
	Dose, mSv	Population, million	excess cancers	Region	Population, million	excess cancers
1	1	311.6	60			
2	7	129.7	125	Vitebsk	1.404	1
3	19	112	300	Grodno	1.156	3
				Minsk	1.562	4
4	63	6.8	60	Minsk City	1.506	13
5	201	12.1	400	Brest	1.417	47
				Gomel	1.670	55
				Mogilev	1.269	42
Total	11	572.2	945		9.984	165

The same method was applied to estimate the number of additional thyroid cancers in Belarus in comparison with the prognosis by Cardis et al.[8]. The results are presented in Table 10.
As can be seen from Table 9 and 10, the model used by Cardis et al. [8] yields 165 additional thyroid cancers in Belarus during 1986-2005 and 2,835 additional thyroid cancers during 1986-2065. As shown above, we determined 663 excess thyroid cancers in children of Belarus, or 4-times more, for a shorter period, 1990-2000. This means that Cardis et al. [8] estimates are far too low. The same conclusion can be drawn with respect to the number of additional thyroid cancers in Belarus, 1986-2065. This is easy to demonstrate by using the second method of assessment.

Table 10. Incidence of thyroid cancer in all European countries and Belarus in 1986-2065 after Cardis et al. [8]

Group	All countries of Europe [8]			Regions of Belarus		
	Dose, mSv	Population, mln.	Number of cancers	Region	Population, mln.	Number of cancers
1	1	311.6	800			
2	7	129.7	1,900	Vitebsk	1.404	21
3	19	112	5,100	Grodno	1.156	53
				Minsk	1.562	69
4	63	6.8	1,100	city Minsk	1.506	244
5	201	12.1	6,800	Brest	1.417	796
				Gomel	1.670	939
				Mogilev	1.269	713
Total	11	572.2	15,700		9.984	2,835

Second method

According to Cardis et al. [8], 437,500 spontaneous thyroid cancers were registered in all affected countries of Europe in 1986-2005, i.e. during 20 years after the Chernobyl accident. This number is divided by the number of person-years (1144·million) accumulated in this period to obtain a time-averaged spontaneous crude rate of thyroid cancers in European countries in 1986-2005 of $3.82 \cdot 10^{-5}$ a^{-1} during 1986-2005. Using this value for Belarus gives 7,731 spontaneous thyroid cancers in Belarus during 1986-2005. The number of thyroid cancers registered in Belarus in this period is 13,075 cases [35]. So there were 5,344 excess thyroid cancers, about 30-times more than the number of additional thyroid cancers that can be estimated by using data of Cardis et al. [8]. The disagreement in real numbers of additional thyroid cancers in Belarus is even higher. The incidence rate of $3.82 \cdot 10^{-5}$ a^{-1} per 100,000 person-years used here for the assessment of the number of expected thyroid cancers on the basis of the second method overestimates the true incidence rate of spontaneous thyroid cancers in Belarus. This is seen from Figures 1 and 2 that give time-averaged crude incidence rates of thyroid cancers in different regions of Belarus as well as in the entire country in 1987-1989.

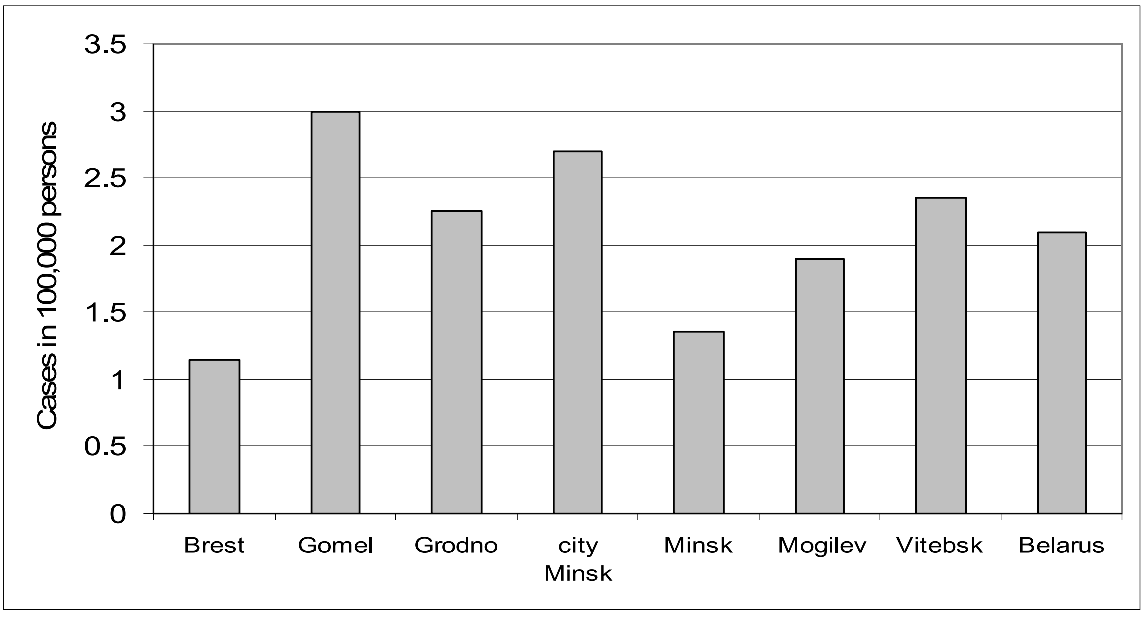

Fig.1. Crude incidence rates of thyroid cancers in regions of Belarus, 1987-1989.

As can be seen from Fig.1, a significant difference in crude incidence rates of thyroid cancers in populations of different regions of Belarus existed already in the first three years after the Chernobyl accident. The incidence rate was highest in Gomel region which suffered the highest fallout from Chernobyl.

Fig. 2 presents time-averaged crude incidence rates of thyroid cancers in different regions of Belarus as well as in the entire country in 1986-2005. For comparison the value $3.822 \cdot 10^{-5}$ a^{-1} assessed as the spontaneous incidence rate in affected European countries for the period 1986-2005 on the basis of data of Cardis et al. [8] is also shown in Fig. 2.

As can be seen from Fig.2 the time-averaged crude incidence rates of thyroid cancers determined for this period show great variations. Again, the incidence rate is highest in Gomel region. The lowest incidence of thyroid cancers is found in Grodno region with relatively low deposition of the isotope ^{131}I. In 1987-1989, the incidence rate of thyroid cancers in Grodno region was similar to the rate in all Belarus. Therefore we use the average incidence rate of $3.37 \cdot 10^{-5}$ a^{-1} for Grodno as expected spontaneous rate in Belarus in 1986-2005.The calculation on the basis of this value gives 6,820 spontaneous thyroid cancers in Belarus for the period 1986-2005. Subtraction of this value from the number of thyroid cancers registered in this period in Belarus (13,075 cases) yields 6,255 radiation-induced thyroid cancers in Belarus, 1986-2005. This is 38-times more than the number of additional thyroid cancers assessed in the present report on the basis of data estimated by Cardis et al. [8[for the period 1986-2005 (165 cases) and more than double than the number of additional thyroid cancers that can be calculated by using data [8] 1986-2065.

Fig.2. Crude incidence rates of thyroid cancers in populations of regions of Belarus (1986-2005) and averaged incidence rate for Europe according to [8].

Third method.

The number of radiation-induced cancers is determined from a comparison of exposed and non-exposed populations. So the rates in Belarus can be compared to the rates in countries with low exposure, but similar gender and age distributions as well as similar conditions of life. Latvia fulfils these requirements and thus can be considered as a reference country by assessment of radiation-induced thyroid cancers in Belarus [33,34]. Fig.7 shows the crude incidence rates of thyroid cancers in Belarus and Latvia. Data for Belarus are given by each year in the period 1985-2005 [34], the data for Latvia only for 1985, 1990, 1995, and 2002

[33].

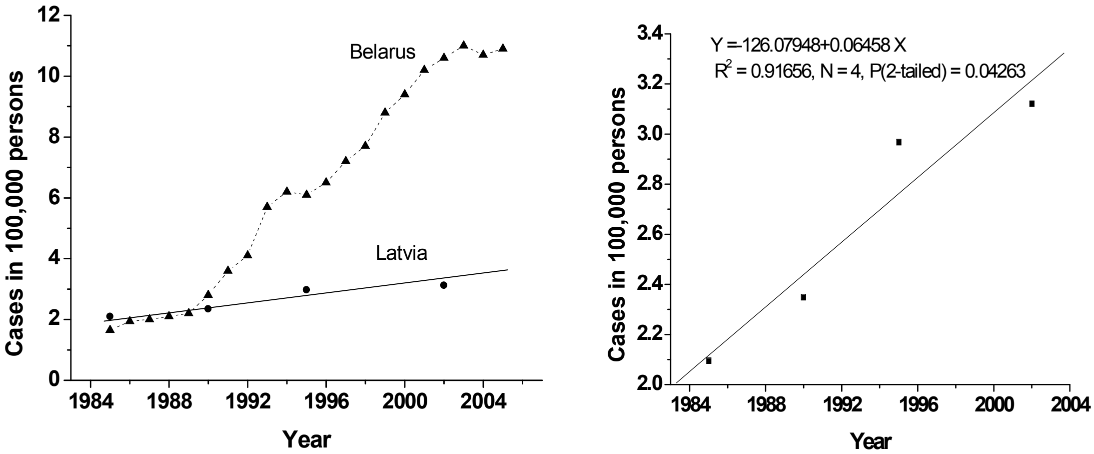

Fig.3. Crude incidence rates of thyroid cancers in Belarus and Latvia.

The crude incidence rates of thyroid cancer agree in the two countries until about 1990. Thereafter, a steep increase occurs in Belarus. The only plausible explanation is the high irradiation of the thyroid gland of the Belarusian population from Chernobyl. Therefore the crude incidence rates of thyroid cancers in Latvia can be used as expected incidence rates in Belarus after 1990. The right panel of Fig.3 demonstrates that the crude incidence rate of thyroid cancers in Latvia in the period 1985-2002 is a linear function of time. Using the linear approximation shown in this panel gives the number of expected thyroid cancers in Belarus in 1986-2005 equal to 5,645 cases. Subtraction of this number from the number of thyroid cancers registered in Belarus in this period (13,075 cases) gives the number of additional thyroid cancers manifested in Belarus in 1986-2005 equal to 7.435 cases. The last number is only 6% smaller than the number assessed with the second method, i.e. on the basis of cases registered in the Grodno region (7,709 cases). This agreement indicates that the number of additional thyroid cancers in Belarus manifested in 1986-2005 is approximately 7,743- 7,709 cases but not 165 cases as follows from the report of Cardis et al. [8].

All these estimations allow us to conclude that the prediction model developed by Cardis et al. [8] for assessment of health consequences of the Chernobyl accident gives fully incorrect values in case of thyroid cancers. However, the analysis undertaken in the present report allows the same conclusion about the incorrectness of the method used in the report [8] for assessment of radiation-induced leukemias and solid cancers other than thyroid and non-melanoma skin cancers. As in case of thyroid cancers the method of Cardis et al. [8] gives very significant underestimation of numbers of these malignant neoplasms. Assessment on the basis of data [8] carried out by using the method described above (first method) gives 218 additional solid cancers other than thyroid cancers and non-melanoma skin cancers for the period 1986-2005 and 1,666 additional cancers of the same type for the period 1986-2065. These values are in full contradiction with reality. Existing data [38] show that approximately 3,280 additional stomach cancers appeared in Belarus in 1986-2001 (95% CI from 2,580 to 3,990 cases). The number of stomach cancers registered in Belarus in this period is about 62,466 cases (59,186 expected cancers). As can be seen from here the number of already manifested stomach cancers in Belarus is higher even than the number of all solid cancers other than thyroid cancers and non-melanoma skin cancers forecasted by Cardis et al. [8] for Belarus for the period 1986-2065.The same situation exists in case of prognoses of additional leukemias made by authors [8] for Belarus. According to this prognosis, 117 additional leukemias manifested in the entire Belarusian population in the period 1986-2005. However, this number is less by a factor of 2 than the number of leukemias that manifested only in children of Belarus in the period 1986-1997 [39]. Assessment of authors [39] show that approximately 237 additional leukemias manifested in children of Belarus in 1986-1997 (95%CI from 143 do 340 cases). The total number of leukemias in children of Belarus registered in this period is 1,117 cases (880 expected cases). The number of acute leukemias in adults of Belarus manifested already after the accident at the Chernobyl NPP was assessed by authors [40] equal to 158 cases. These data show that the method used by Cardis et al. [8] causes a significant underestimation of additional thyroid cancers, additional solid cancers other than thyroid cancers and non-melanoma skin cancers as well as additional leukemias.

It is evident that any method of prediction can be justified only when it correctly describes already manifested effects. As it was demonstrated in the present report, the method developed by Cardis et al. [8] can not fulfill this requirement. This means that method of Cardis et al. [8] can not be justified for assessment of health effects that can manifest in countries affected by the Chernobyl accident.

Two reasons could be responsible for the low estimates of excess cancers reported by Cardis et al. [8] assumed radiation doses or low radiation risk factors. But the thyroid dose of 10^6 PGy for Belarus reported by Cardis et al. [8] is close to the dose of 940,000 PGy used in the present report.
The same is true for doses used to estimate the excess of solid cancers other than thyroid and non-melanoma skin cancers, as well as for excess leukaemia cases.

For their assessment of the excess incidence and mortality rates of cancers in Europe, Cardis et al [8] used the method described in BEIR-VII [3]. This method uses the Life Attributable Risk determined for atomic bomb survivors, together with a dose and dose rate efficiency factor (DDREF) of 1.5 for the estimate of excess solid cancers. A DDREF of 1, however, was used by Cardis for estimating the number of excess leukaemia cases.

It is evident that the main reason for the discrepancy between our results and those obtained by Cardis et al. [8] is that the extrapolation of the risk determined in Japanese atomic bomb survivors underestimates the risk of chronic radiation exposure at low dose rates [41].
Recent epidemiologic studies provide evidence that the radiation risk from chronic irradiation is higher than the radiation risk determined from the Japanese atomic bomb survivors. This was established for Russian liquidators [42]. The similar data were found for inhabitants of rural villages bordering the Techa River in the Urals, Russia. They were exposed to high radiation doses after an accident in a reprocessing facility in the early 1950's. The excessive relative risk (ERR) of mortality from solid cancers for this group of people was estimated as 0.92/Gy [44], more than twice the risk of 0.42/Sv for mortality from radiation-induced solid cancers established for atomic bomb survivors [43].

A recent study of cancer mortality in Semipalatinsk region (Kazachstan) whose inhabitants were suffering from the fallout from nearby Soviet atmospheric nuclear weapons tests [45] yielded an ERR of 1.77/Sv (95%CI from 1.35 to 2.27). This is 4-times the radiation risk of mortality from solid cancers of atomic bomb survivors.

In 2005, Cardis et al. [46,47] studied the risk of radiation induced cancers in workers of the nuclear industry. The study included 407,391 workers (5,192,710 person-years) at nuclear facilities who were monitored for external irradiation. The recorded collective dose was 7,892 PSv). An excessive relative risk (ERR) of mortality from all cancers excluding leukaemia of 0.97/Gy was found (95% CI from 0.14 to 1.97). The ERR of mortality from all solid cancers was estimated in the 15-Country Study as 0.87/Gy (95% CI from 0.03 to 1.88).

It is important to notice here that these coefficients reflect radiation risks of men because 98% of the collective dose of nuclear industry workers was delivered to men [46,47]. But it is known that the excessive relative risk of cancers in men is lower than in women. According to Preston et al. [43,48], the excessive relative risk of fatal solid cancers in atomic bomb survivors exposed at age 30 is 0.55/Sv for females and 0.29/Sv for males, i.e. the risk for women is 1.9-times higher than for men. The ERR of a mixed population of men and women is therefore expected to be higher by a factor of 1.45 as the risk for men. With ERR=0.87/Sv for male radiation workers we then expect ERR=1.26/Sv as the average risk for a mixed population of healthy men and women at similar age at irradiation as nuclear workers. In the general population, including children and sick people, the risk is expected to be higher than ERR=1.26/Sv which was derived from the risk of healthy 30 year old male nuclear workers.Therefore, the use of risk factors recommended by ICRP, which are based on the results for the Japanese atomic bomb survivors, will lead to a substantial underestimation of the expected health effects from the Chernobyl accident. An assessment based on a relative radiation risk of ERR=1.26/Sv for a mixed population, an expected cumulated number of 117,4 Mio cancer cases until 2065, and an average individual dose of 0.5 mSv, yields 74,000 excess cancer cases, 5-times more than the 14,100 fatal cancers predicted by Cardis. A similar calculation for thyroid cancers and leukaemia cases yields 74,700 excess thyroid cancers and 8,960 additional fatal leukaemia cases expected in Europe in 1986-2065 as a result of the Chernobyl accident. These numbers are compatible with our results of 92,600 excess thyroid cancers and 9,100 excess leukaemia during 1986-2056.

As mentioned above, significant disagreements also exist between the numbers of excess cancer cases estimated in the present report and in the report of Gofman [4]. It can be shown that Gofman used unrealistic collective doses and high radiation risk factors. For a mean ground deposition of ^{137}Cs of 1,075 Bq/m^2 in Denmark, Gofman calculated a cumulated radiation whole-body dose from isotopes ^{134}Cs and ^{137}Cs of 20.8 millirads from external and internal exposure. He did not consider other isotopes of the Chernobyl origin because only caesium was measured. This dose, divided by 1,075 Bq/m², gives 19,35 millirads per 1,000 Bq ^{137}Cs per m². We used this risk factor, together with data of the caesium-137 ground deposition [2], to determine the collective doses in all affected countries of the world. Data of the size of territories and populations of affected countries are provided in [1]. The estimated doses were then multiplied by the radiation risk for fatal solid cancers used by Gofman (1 fatal case per collective dose 268,000 person-millirad). The calculation yielded 253,800 instead of 475,000 fatal solid cancers reported by Gofman. With a smaller risk factor assessed later by Gofman [49] (25.56 cases by irradiation of 10,000 persons with the dose 1 cSv) we obtain 122,700 excess cancer cases, 4-times less than published in [4]. A similar reduction can be shown for fatal leukaemia.

Our corrections lead to significant changes in the numbers of additional fatal cancers and leukaemia cases in some countries of Europe. For Romania, e.g., Gofman calculated 66,000 additional fatal solid cancers, many more than for Belarus (26,400 cases). This is not plausible. With correct data of the caesium deposition the number of excess cancers in Romania decreases from 66,000 cases to 10,422 cases. Using the revised risk [49[reduces the number of fatal cancers in Romania to 5,040, i.e. by a factor of 13 compared to the original estimate. In Germany, the original number of excess cancers by applying the same procedure decreases from 52,200 to approximately 9,000 cases. Similar reductions are found for Poland, Ukraine, and other countries.

Table 11. Additional incidence and mortality from malignant neoplasms in affected countries of Europe as a result of the Chernobyl accident.

Thyroid	Solid cancers	Leukaemia	Combined	Time period	Sources
		Incidence			
74,700	118,780***	15,886****	209,366	1986-2065	[8]*
92,600 (44,000-141,200)	130,400 (42,900-217,900)	12,900 (2,800-23,000)	226,900	1986-2056	This report
		Mortality			
	122,700	11,200	133,900	Infinite time	[4]*
21,215**	74,000	8,960	104,175	1986-2065	[8]*
26,300 (12,500 ÷ 40,100)	81,300 (23,000 ÷ 139,500)	9,100 (1,480 ÷ 16,700)	116,700	1986-2005	This report

* Values corrected in the present report.
** Estimated by multiplying the number of assessed additional thyroid by coefficient 0.284.
*** Estimated by multiplying the number of assessed additional solid cancers by coefficient 0.623.
**** Estimated by multiplying the number of assessed additional leukaemia cancers by coefficient 0.705.

Table 11 compares our estimates with the estimates by Cardis et al .[8] and Gofman [4] corrected in the present report. As can be seen, the corrected numbers agree reasonably well.

Discussion

The analysis carried out in the present report showed that the radiation risk of chronic exposure to ionising radiation at low doses and dose rates is higher than anticipated before the Chernobyl accident. The observed increases of cancer rates in Belarus suggest that the official risk factors, derived from data of the Japanese atomic bomb survivors, are likely to underestimate the radiation risk by at least a factor of three. The method of risk transfer applied in the present study can be a useful tool in a situation where exact information about dose and radiation risk is not available.

The results of the present study show that the radiation risk of chronic irradiation at low doses and low dose rates is higher than the radiation risk of acute irradiation. Therefore, the radiation risk of acute irradiation must not be used for the assessment of possible health effects from chronic radiation. Using the radiation risk derived from the Japanese atomic bomb survivors for populations exposed to radiation from the Chernobyl accident will result in a considerable underestimation of the expected effects. The use of a DDREF factor greater than 1 will additionally aggravate the problem. At present we do not know why the radiation risk for chronic radiation at very low doses and dose rates - as was the case of radiation exposure from Chernobyl - is higher than for acute radiation. There might be a difference in the biological effect of the high energy gamma radiation of an atomic bomb [50] and the lower gamma energies of most radioisotopes like caesium. Also, a substantial part of the radiation burden from Chernobyl came from incorporated α and β emitters.

The method developed in the present report can be used at least for a qualitative estimation of additional cancers in case of normal populations irradiated chronically at very low doses and very low dose rates. The advantage of this method is that it does not require correct coefficients of radiation risks and correct values of doses.

The Chernobyl accident will cause approximately 100,000 additional fatal cancers in Europe during 1986-2056. But the method has severe limitations due to the ecological study design. Thus the numbers of additional cancers in the affected European countries predicted in the present report have only qualitative character. The precision of these numbers depends critically on the number of additional cancers in Belarus. The longer the follow-up time, the better is the data base to determine the number of excess cases in Belarus, which in turn will improve the prediction of excess cases in Europe.

In most countries any excess rates are expected to be in the range of spontaneous variations. Some radiation experts might use this fact to deny any radiation effects in countries outside the former Soviet Union. They might also doubt the quality of the data and the methods of data processing. But in Belarus the increase of cancers after the Chernobyl accident is so large that it is visible even without using sophisticated statistical methods. Not to learn from the data in Belarus, Ukraine, and Russia will lead to a significant underestimation of the number of excess cancer cases in the rest of Europe.

It should be mentioned that the adverse health effects are not the only consequences of the Chernobyl accident. It also caused significant economical losses in many affected countries. They are especially high in Belarus. Belarusian specialists estimated the economical loss as 235 billion US$ during 1986-2015 [51]. This is approximately 8-times the gross domestic product of Belarus in 2004 [52]. 190 billion US$ or about 80% of the total cost will be used for radiation protection measures [51].

The accident at the Chernobyl NPP was devastating for Belarus. It caused the relocation of a large number of people in Belarus. According to [53], 24,725 persons were evacuated from May to September 1986. During 1991-1998, another 110,000 persons were resettled from highly contaminated areas to so called clean territories of Belarus [53]. Evacuation and resettlement were performed with financial and material support of the Belarusian government. Until 2000, another approximately 200,000 persons moved without any government support [54]. Altogether, at least 335,000 persons in Belarus lost their places of living and their properties. This exodus of inhabitants of contaminated areas of Belarus is surprising because in Soviet times and even after the break-up of the Soviet Union any internal and external migration was under strong control of the authorities. There is no doubt that a similar nuclear accident in a country of Western Europe, e.g. Belgium, France, or Germany, would prompt millions of people to leave the contaminated areas. This makes accidents at nuclear power plants much more dangerous than accidents at conventional power plants. In the case of severe accidents in conventional power plants we might expect some dozens of victims among the operational staff. In contrast, if an accident similar to the Chernobyl accident took place in a densely populated area, we must face hundreds of thousands of victims.

At present, the possibility of accidents like the Chernobyl accident cannot be excluded for any nuclear reactor in operation because all nuclear reactors contain a supercritical mass of fissionable material. In case of an accidental or intentional nuclear explosion, leading to the release of a huge amount thermal energy, every existing reactor will be destroyed, not only a Chernobyl type reactor. Such an explosion occurred in the former Soviet Union more than 8 months before the Chernobyl accident when an uncontrolled chain reaction occurred in the active zone of a pressurized water reactor in a submarine [55,56]. This accident happened on August 10, 1985, during reloading of nuclear fuel. An error of an operator caused an uncontrolled chain reaction and the explosion of the reactor core. Thus, accidents with similar consequences can also occur in Western pressurized water reactors.

Attempts to play down the consequences of the accident at the Chernobyl nuclear power plant are dangerous for the general public and for the nuclear industry. Such attempts decrease the efforts to improving the safety of nuclear reactors operating in many countries and could cause a second Chernobyl somewhere in the world. The accident at the Chernobyl NPP revealed the high potential danger of nuclear power plants.

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