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RADIATION EXPOSURE TO THE POPULATION OF EUROPE FOLLOWING THE CHERNOBYL ACCIDENT

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On the occasion of the 20th anniversary of the Chernobyl accident an attempt has been made to evaluate the impact of the Chernobyl accident on the global burden of human cancer in Europe. This required the estimation of radiation doses in each of the 40 European countries. Dose estimation was based on the analysis and compilation of data either published in the scientific literature or provided by local experts. Considerable variability has been observed in exposure levels among the European populations. The average individual doses to the thyroid from the intake of ^{131}I for children aged 1 y were found to vary from ~0.01 mGy in Portugal up to 750 mGy in Gomel Oblast (Belarus). Thyroid doses to adults were consistently lower than the doses received by young children. The average individual effective doses from external exposure and ingestion of long-lived radiocaesium accrued in the period 1986–2005 varied from ~0 in Portugal to ~10 mSv in Gomel Oblast (Belarus) and Bryansk Oblast (Russia). The uncertainties in the dose estimates were subjectively estimated on the basis of the availability and reliability of the radiation data that were used for dose reconstruction in each country.

INTRODUCTION

On 26 April 1986 an accident occurred at the Chernobyl power plant located in north-western Ukraine close to the border with Belarus. Following this, the most severe nuclear accident to date, large amounts of radioactive materials were released into the atmosphere from the destroyed nuclear reactor, including $(1.2-1.8) \times 10^{18}$ Bq of ^{131}I, and $\sim 1.4 \times 10^{17}$ Bq of long-lived ^{134}Cs and ^{137}Cs[1]. Atmospheric transport of these and other radionuclides caused serious contamination in Belarus and in Ukraine, as well as in the western part of the Russian Federation close to the Chernobyl power plant. The radioactive debris from the power plant was also widely dispersed over much of the territory of Europe[2]. On the occasion of the 20th anniversary of the accident, an attempt has been made to evaluate possible impact of the accident on the burden of human cancer among the European population[3]. One of the main aspects of this evaluation was the prediction of the number of cancer cases that might be attributed to the Chernobyl accident up to now and in the future. This required the estimation of radiation doses for each country in Europe.

The doses received during the first year after the accident were evaluated in most European countries shortly after the accident; the results are summarised in reports published in 1987 by NEA[4] (for member countries of the Organisation for Economic Co-operation and Development) and in 1988 by UNSCEAR[5] (for all of Europe). Since that time, however, numerous measurements of radiation in the environment, in foodstuffs and in humans have been carried out, including a comprehensive monitoring programme developed to prepare an Atlas of ^{137}Cs deposition in Europe after the Chernobyl accident[2]. In addition, metabolic models describing the biokinetics of radionuclides in man have improved since 1987–1988 and revised dose coefficients for inhalation[6] and ingestion[7] as well as conversion factors for external exposure[8] have become available. Political changes have also occurred towards the end of the past century, leading to the creation of new independent states in Europe and to the release of additional information on radiological

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measurement data, notably in Belarus, Russia and Ukraine. For all these reasons, there was a need to update the estimates of exposure summarised in the UNSCEAR 1988 Report(5).

This paper focuses on 40 European countries: Albania, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Macedonia, Malta, Moldova, the Netherlands, Norway, Poland, Portugal, Romania, the Russian Federation, Serbia and Montenegro, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine and the United Kingdom. These countries constitute the whole of what is defined geographically as Europe, excluding, however, the Caucasus, Turkey, Andorra and San Marino. In the Russian Federation, only the four most contaminated Oblasts (Bryansk, Kaluga, Orel and Tula, which represent only a small fraction of the territory of that country) are included. The following doses were re-evaluated:

(1) age-dependent thyroid doses from the intake of ^{131}I via inhalation and ingestion within 2 months after the accident;
(2) whole-body doses for adults from the intake of ^{134}Cs and ^{137}Cs for the period from 1986 to 2005 as well as projected doses up to 2065; and
(3) whole-body doses for adults due to external irradiation from radionuclides deposited on the ground for the period from 1986 to 2005 as well as projected doses up to 2065.

METHODS

To obtain the best possible dose estimates, attempts were made to contact experts in all European countries (except Bosnia and Herzegovina, Liechtenstein and Luxembourg). For different reasons, only a limited number of local experts agreed to participate in the study. The methods of dose estimation were tailored to the types of radiation data available in each particular country. Local experts provided dose estimates for Belarus, Ukraine and the Russian Federation, where extensive work has been undertaken developing and validating methods for dose reconstruction(9–23). For less affected European countries, information on country-specific radiation data and dose estimates was either obtained from local experts: Bulgaria, the Czech Republic, Finland, Lithuania and Switzerland; and/or from published data: Austria(24–28), Belgium(29), Bulgaria(30), Croatia(31,32), the Czech Republic(33,34), Estonia(35), Finland(36), France(37), Greece(38,39), Hungary(40), Italy(41,42), Lithuania(43,44), Norway(45,46), Serbia and Montenegro(47), Slovakia(48,49), Sweden(50), Switzerland(51) and the United Kingdom(52,53).

Data on ^{137}Cs deposition density and time-integrated activity of ^{131}I and ^{137}Cs in foodstuffs during the first year after the accident were taken from the Atlas on ^{137}Cs deposition in Europe(2) and from the 1988 UNSCEAR Report(5), respectively. This information, together with the data on population size and structure in 1986–2005(54), dose coefficients for inhalation(6) and ingestion(7), and conversion factors for external exposure(8), was used to estimate doses. Although a large variability of exposures due to the Chernobyl fallout has been observed within some countries in Europe (i.e. Greece, France, Switzerland, Norway, Sweden, etc.), this study focuses on the evaluation of country-wide average doses for each country. However, in Belarus, Russia and Ukraine, doses were also estimated for the most contaminated regions in these countries. For some countries (Albania, Bosnia and Herzegovina, Iceland, Macedonia, Malta, Moldova) input data were very limited or were not available at all. Therefore, interpolation between neighbouring countries was applied to derive the necessary data, wherever it was possible.

Ground deposition of radionuclides

The radioactive debris released into the atmosphere was widely dispersed over the territory of Europe, with the highest levels of ground contamination in Belarus, Ukraine and the western part of the Russian Federation. Outside these most affected regions, the contamination levels were, in general, much lower. With respect to internal exposure, the most important radionuclides were ^{131}I, ^{134}Cs and ^{137}Cs. ^{134}Cs and ^{137}Cs were the most important radionuclides for external exposure, although a number of other radionuclides, particularly ^{95}Zr–Nb, ^{103}Ru, ^{106}Ru, ^{131}I, ^{132}Te–I and ^{140}Ba–La, contributed to a varying extent to the dose from external irradiation shortly after deposition on the ground.

The deposition density of ^{137}Cs on the ground is the only quantity that could be reliably measured years after the Chernobyl accident. A comprehensive monitoring programme of ^{137}Cs deposition was conducted between 1992 and 1996 in all of Europe, with the exception of Albania, Bosnia and Herzegovina, Bulgaria, Macedonia, Serbia and Montenegro and Iceland. As a result, an Atlas of ^{137}Cs deposition in Europe after the Chernobyl accident was prepared(2). This information, together with data on the radionuclide composition of the deposited activity that was measured shortly after the accident was the basis of the dose assessments.

Country-wide average deposition densities of ^{137}Cs from Chernobyl fallout and ratios of activities of selected radionuclides to activity of ^{137}Cs in deposition are given in Table 1 for European countries. For some countries, data on deposition of ^{99}Mo,

Table 1. Country/region-wide average deposition densities of ^{137}Cs from Chernobyl fallout and ratio of activity of selected radionuclides to activity of ^{137}Cs in deposition observed in European countries.

Country	^{137}Cs deposition density[2] (kBq m^{-2})	Ratio of activity to ^{137}Cs in deposition at the time of the main deposition[5]						
		^{95}Zr	^{103}Ru	^{106}Ru	^{131}I	^{132}Te	^{134}Cs	^{140}Ba
Albania[a]	7.2	0.1	2.5	0.6	3.8	7	0.5	1.5
Austria	18.7[24]	—	1.3	0.46[24]	5	4.8	0.57[24]	—
Belarus, Brest Oblast[23]	18.2[55]	0.5–0.8	2.2–2.8	0.7–0.9	19–23	7.6–12	0.5	1.5–2.1
Belarus, Vitebsk Oblast[23]	1.1[55]	0.2	1.8	0.4	24	4.8	0.5	0.8
Belarus, Gomel Oblast[23]	154[55]	0.17–4	1.6–3.7	0.42–1	8.3–21	4.2–11	0.5	0.76–7.6
Belarus, Grodno Oblast[23]	8[55]	0.5	2.8	0.7	23	12	0.5	1.5
Belarus, Minsk Oblast[23]	5.8[55]	0.5	2.8	0.7	23	12	0.5	1.5
Belarus, Minsk-City[23]	6.2[55]	0.3	1.5	0.45	14	2.8	0.5	1
Belarus, Mogilev Oblast[23]	61[55]	0.17–4	1.6–2.4	0.3–0.9	8.3–21	4.2–11	0.5	0.76–7.6
Belgium	0.3	—	1.7	0.5	6.2	4	0.55	1.6
Bosnia and Herzegovina	6.4	—	1.4	0.3	5.9	7.2	0.4	0.7
Bulgaria[56]	7	0.14	1.4	0.36	1.7	4	0.5	1.6
Croatia[31]	3.7	0.14	2.6	1	3.3	6.1	0.4	0.7
Cyprus	0.6[5]	—	—	—	3.3	—	0.55	—
Czech Republic[57]	4.7	—	1.9	0.3	13.8	5.1	0.5	1.0
Denmark	0.36	—	1.5	0.5	4.7	4.3	0.55	—
Estonia[b]	2[19]	1.1	2.2	0.5	4.2	5.9	0.6	0.7
Finland[c] [58]	12.2	1.7	2.2	0.5	4.2	5.9	0.6	0.7
France	0.7	—	1.4	0.3	7.3	4.8	0.55	—
Germany	2.8	—	1.5	0.3	5.8	6.8	0.55	—
Greece[38]	5.2[38]	0.1	2.5	0.6	3.8	7	0.5	1.5
Hungary	1.9	—	2.5	0.6	6.2	6.7	0.55	—
Iceland	0.3	—	—	—	—	—	0.55	—
Ireland	3.1	—	1.5	0.4	3.1	3.4	0.55	0.8
Italy	2.1	—	2	0.55	4	7.8	0.55	—
Latvia[d]	0.85	0.2	1.8	0.4	24	4.8	0.5	1.5
Liechtenstein[e]	11.8[26]	—	1.3	0.46	5	4.8	0.57	—
Lithuania[59]	3.7	0.4	1.5	—	23	12	0.55	0.72
Luxembourg	1.2	—	1.7	0.5	7	4	0.55	—
Macedonia	8.5[f]	—	1.5	0.3	6	7.6	0.4	—
Malta[g]	1.9	—	1.8	0.5	3.8	8.5	0.55	—
Moldova	10.1	—	2.9	0.7	5.2	6.4	0.55	—
Netherlands	0.3	—	1.9	0.5	6.3	3.3	0.55	—
Norway	4.7	—	2	0.5	16	2.6	0.55	—
Poland	1.3	—	2.5	0.3	7.3	8.4	0.55	—
Portugal	0.02	—	2	0.6	3.5	0.2	0.55	—
Romania	6.5	—	2.9	0.7	5.2	6.4	0.55	—
Russia, Bryansk Oblast[60]	110[61]	0.07–0.14	1.6	0.45	7.6–11	6.7–10	0.54	0.41–0.63
Russia, Kaluga Oblast[60]	14.2[61]	0.07	1.5	0.42	7.7	6.3	0.5	0.48
Russia, Orel Oblast[60]	41[61]	0.07	1.6	0.43	8.1	7.1	0.5	0.49
Russia, Tula Oblast[60]	67[61]	0.07	1.6	0.46	7.9	6.5	0.5	0.5
Serbia and Montenegro	9[47]	—	1.5	0.3	6	7.6	0.55	—
Slovakia	3.6	—	1.8	0.3	11	7.3	0.50	—
Slovenia	16.3	—	1.4	0.3	5.9	7.2	0.4	—
Spain	0.06	—	1.5	0.3	3.9	—	0.55	—
Sweden	4.6	—	2	0.78	15.9	1.1	0.55	—
Switzerland	5.6	—	1.9	0.6	7	8.6	0.55	—
Ukraine, Chernihiv Oblast[c] [11]	~15[h]	2	8	2	13	20	0.5	2
Ukraine, Kyiv Oblast[c] [11]	~30[h]	2	8	2	13	20	0.5	2
Ukraine, Kyiv-City[c] [11]	~15[h]	2	8	2	13	20	0.5	2
Ukraine, Rivno Oblast[c] [11]	~40[h]	2	8	2	13	20	0.5	2
Ukraine, Zhytomir Oblast[c] [11]	~50[h]	2	8	2	13	20	0.5	2
Ukraine, remainder[c] [11]	~20[h]	2	8	2	13	20	0.5	2
United Kingdom	0.9	—	1.8	0.6	7.1	12.9	0.55	—

[a]Interpolation between Greece and Serbia and Montenegro
[b]Ratios are assumed to be the same as in Finland
[c]Ratios are decay corrected to 26 April 1986
[d]Ratios are assumed to be the same as in Vitebsk Oblast in Belarus
[e]Ratios are assumed to be the same as in Austria
[f]Interpolation between northern Greece and Serbia and Montenegro
[g]Assumed to be the same as in southern Italy
[h]Derived from Ref. (14)

^{136}Cs, ^{141}Ce, ^{144}Ce and ^{239}Np were also available and used for the reconstruction of external doses.

Dose estimates provided by local experts

As mentioned above, local experts from Belarus, Bulgaria, the Czech Republic, Finland, Lithuania, the Russian Federation, Switzerland and Ukraine provided dose estimates for their countries. These estimates are the results of extensive national dose reconstruction programmes. Dosimetry models used for dose reconstruction included empirical and semi-empirical approaches that are based on the relationships between environmental contamination and measured levels of radionuclides in humans, and ecological models that describe the processes of transfer of radionuclide activities from ground deposition to the human body. Input data used for dose reconstruction in these countries included hundreds of thousands of results of measurements of ^{131}I in human thyroids performed in 1986(9,15,21,30,34); and ^{137}Cs body burdens, as well as, ^{137}Cs in milk and other foodstuffs(10,13,14,19,23,33,62–64). Majority of these measurements were carried out in the most contaminated states.

For other countries, the dose estimates were based on the input data and methods described below.

Internal doses due to inhalation

The internal organ doses for a person in age group k arising from inhalation of air contaminated with ^{131}I and ^{134,137}Cs during radioactive cloud passing were calculated as:

$$D_{i,k}^{\mathrm{inh}} = C_i^{\mathrm{air}} \cdot \left[F_{\mathrm{in}} \cdot \mathrm{RF}^{\mathrm{air}} + (1-F_{\mathrm{in}})\right] \cdot V_k^{\mathrm{air}} \cdot \mathrm{DF}_{i,k}^{\mathrm{inh}}, \quad (1)$$

where $D_{i,k}^{\mathrm{inh}}$ is the internal dose arising from inhalation of radionuclide i (mSv); C_i^{air} is the time-integrated concentration of radionuclide i in outdoor air (Bq d m^{-3}); $F_{\mathrm{in}} = 0.6$ is the indoor occupancy factor(18), unitless; RF$^{\mathrm{air}}$ is the reduction factor that associated with indoor occupancy, unitless; V_k^{air} is the breathing rate of persons in age group k(65) (m^3 d^{-1}); $\mathrm{DF}_{i,k}^{\mathrm{inh}}$ is the inhalation dose coefficient for thyroid (in the case of inhalation of ^{131}I) and for effective dose (in the case of inhalation of ^{134}Cs and ^{137}Cs) for persons in age group k(6) (mSv Bq^{-1}).

The time-integrated concentrations of ^{131}I, and ^{134}Cs and ^{137}Cs in outdoor air are given in Table 2. The values used in the dose calculation were taken from the UNSCEAR 1988 Report(5) or from published data, and were derived from the data bank of Radioactivity Environmental Monitoring at the CEC Joint Research Centre Ispra(66). The reduction factor that associated with indoor occupancy was taken to be 0.5(69).

Internal doses due to ingestion

The internal organ doses for a person in age group k arising from ingestion of ^{131}I and ^{134,137}Cs in contaminated foodstuffs were calculated as:

$$D_{i,k}^{\mathrm{ing}} = C_{i,k}^{\mathrm{diet}} \cdot \mathrm{DF}_{i,k}^{\mathrm{ing}}, \quad (2)$$

where $D_{i,k}^{\mathrm{ing}}$ is the internal dose arising from ingestion of radionuclide i (mSv); $C_{i,k}^{\mathrm{diet}}$ is the yearly integrated activity intake of radionuclide i by ingestion (Bq); $\mathrm{DF}_{i,k}^{\mathrm{ing}}$ is the ingestion dose coefficient for thyroid (in the case of ingestion of ^{131}I) and for effective dose (in the case of ingestion of ^{134}Cs and ^{137}Cs) for persons in age group k(7) (mSv Bq^{-1}).

Internal doses due to ingestion in 1986

Consumption of milk, milk products and leafy vegetables was considered for ^{131}I intake. No delay between the production and the consumption of milk was assumed for rural inhabitants, while for people living in urban areas the delay from milking to consumption was taken to be 1 d. The age-dependent dietary intake of ^{131}I that was taken from the UNSCEAR 1988 Report(5) and scientific publications and used in calculations is given in Table 2.

Consumption of milk and milk products, leafy vegetables, grain products, other fruits and vegetables, and meat was considered for ingestion of radiocaesium. The UNSCEAR 1988 Report(5) and data available in scientific publications were used as the sources of information for radiocaesium intake. In the estimation of the time-integrated concentrations of ^{137}Cs in 1986 (from the time of the accident to the end of the year), the time-integrated concentrations of ^{137}Cs given in the UNSCEAR 1988 Report(5) for the first year after the accident were multiplied by 0.65. This reduction factor was derived from the results of measurements of ^{137}Cs concentration in skim milk powder taken in Austria(26). The country-specific initial activity ratio of ^{134}Cs to ^{137}Cs in deposition (see Table 1) was applied to estimate the intake of ^{134}Cs with diet.

Internal doses due to ingestion during the following years

The time-integrated activity dietary intake of ^{137}Cs in 1987 and 1988 were estimated from the integrated activity of dietary ^{137}Cs in 1986 using reduction factors of 0.65 and 0.25, respectively. These reduction factors were derived from the measurements of ^{137}Cs activity concentration in skim milk powder taken in Austria(26). For later years, the dietary intake of ^{137}Cs was assumed to decrease exponentially with a half-time of 1.7 y up to 1993 and with a half-time of

Table 2. Country/region-wide average integrated activity of radionuclides in air and in diet[5].

Country	Integrated activity in air (Bq d m^{-3})			Yearly integrated activity in diet (Bq) of			
				^{131}I for age group		^{137}Cs in year	
	^{131}I	^{134}Cs	^{137}Cs	1 y	20 y	1986	1987
Albania[a]	50	4	8	2570	6330	2690	1750
Austria	115[66]	6.4[66]	11.2[66]	2280	1650	11,700[27]	7600
Belgium	30	2	5	560	730	420	270
Bosnia and Herzegovina	72	3.4	7.4	5050	12,900	2200	1430
Bulgaria	13.8[56]	4.4[56]	9[56]	4590[30]	7150[30]	8560	5560
Croatia	61[31]	12[31]	28[31]	5890[32]	11,500	7790[32]	5060
Cyprus	20	3.5	7	1260	2460	1140	740
Czech Republic	140[66]	5.2[66]	10.5[66]	3160	3600	1670[33]	1090
Denmark	6.7[66]	0.26[66]	0.53[66]	30	32	430	280
Estonia	55[66]b	1[66]b	1.7[66]b	620	1380	1060	690
Finland	47[67]	0.9[67]	1.5[67]	150[64]	150[64]	4200[68]	7300[68]
France	7.9	0.52	1.2	590	610	1070	700
Germany	42	3.2	6.1	580	590	1500	970
Greece	40[38]	5[38]	10[38]	4930	4540	12,900[38]	8390
Hungary	29	2.1	4.2	1570	1650	3980	2580
Ireland	1.0	0.06	0.11	650	940	1970	1280
Italy	35	2.2	4.2	2260	2650	5900	3840
Latvia	55	1	1.7	1400[c]	3460[c]	850[c]	320[c]
Liechtenstein	43[66]	4.4[66]	8[66]	2400	1710	7300[d]	4800[d]
Lithuania	270[44]	4.4	8.8	6250[44]	4300[44]	3600[59]	510[59]
Luxembourg	30	2	5	670	870	1440	930
Macedonia	57	2.5	5.9	2570	6380	2690	1750
Malta[e]	26	1.6	2.7	2100	1480	5050	3280
Moldova[f]	340	8	17	5380	7950	10,630	6900
Netherlands	20[66]	0.9[66]	1.9[66]	230	630	760	490
Norway	85	2.8	5.3	175	260	3940	2560
Poland	72	4.1	8.2	2120	1750	4260	2770
Portugal	0.07	0.01	0.02	2	5	40	30
Romania	180	6.4	13.7	4660	4120	6880	4470
Serbia and Montenegro	57	2.5	5.9	2550	6290	3020	1960
Slovakia	110[66]	5.8[66]	10.7[66]	4720	4540	5150	3350
Slovenia	72	3.4	7.4	5620	14,400	5600	3640
Spain	0.14	0.015	0.03	30	45	160	100
Sweden	26	0.56	1	220	270	2660	1730
Switzerland	29[66]	1.9[66]	3.8[66]	950[51]	4500[51]	4190[61]	5150[61]
United Kingdom	5.4[66]	0.48[66]	0.9[66]	180	180	530	340

[a]Interpolation between Greece and Serbia and Montenegro
[b]Assumed to be the same as in Helsinki
[c]Assuming the same transfer factors as in Vitebsk Oblast in Belarus
[d]Assuming the same transfer factors as in Austria
[e]Assumed to be the same as in southern Italy
[f]Assumed to be the same as northeastern Romania

7.8 y starting from year 1993. Figure 1 shows the time-dependence of dietary intake of ^{137}Cs activity used in dose reconstruction (solid line) and that observed in Austria[27,28], Belarus[23], the Czech Republic[34], Finland[36] and Norway[46]. As can be seen from Figure 1, the accepted time-dependence of dietary intake of ^{137}Cs agrees with that observed in those countries.

External doses from radionuclides deposited on the ground

The effective doses due to external irradiation from radionuclides deposited on the ground surface were calculated as:

$$D^{\mathrm{ext}} = [F_{\mathrm{u}} \cdot \mathrm{BF}_{\mathrm{u}} + (1 - F_{\mathrm{u}}) \cdot \mathrm{BF}_{\mathrm{r}}] \cdot \sum_i \int_{t_1}^{t_2} H_i(t)\,\mathrm{d}t, \quad (3)$$

where D^{ext} is the effective dose from external irradiation from radionuclides deposited on the ground (mSv); F_{u} is the fraction of urban population in the country[54], unitless; BF_{u} and BF_{r} are behavioural factors that take into account the fraction of time spent indoors and the shielding provided by building materials, for the urban and the rural populations, respectively, unitless; $H_i(t)$ is the external effective

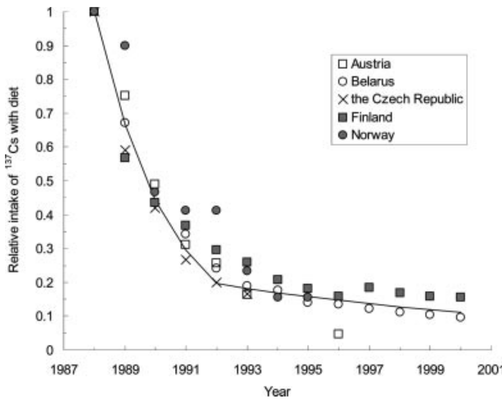

Figure 1. Time-dependence of dietary intake of ^{137}Cs activity: accepted in calculation (solid line) and observed in Austria[27,28] (open squares), Belarus[23] (open circles), the Czech Republic[34] (crosses), Finland[36] (closed squares) and Norway[46] (closed circles).

dose rate due to radionuclide i deposited on the ground surface (mSv d^{-1}); t_1, t_2 are times corresponding to the beginning and the end of the years that are considered (d).

The external effective dose rate due to radionuclide i deposited on the ground surface was calculated as follows:

$$H_i(t) = \sigma_i(t) \cdot r(t) \cdot \mathrm{CF}_i^{\mathrm{ext}}, \tag{4}$$

where $\sigma_i(t)$ is the deposition density of radionuclide i at time t after the accident (kBq m^{-2}); $r(t)$ is an attenuation function that reflects the decreasing dose rate with time due to the migration of the deposited activity to deeper layers of soil, unitless; $\mathrm{CF}_i^{\mathrm{ext}}$ is the conversion factor for radionuclide i from the activity deposited per unit area of ground (as a plane source on the ground surface) to the effective dose rate for an adult (mSv d^{-1} per kBq m^{-2}).

The ground deposition of radionuclide i was derived from the ground deposition of ^{137}Cs as follows:

$$\sigma_i(t) = \sigma_{^{137}\mathrm{Cs}}(t) \cdot R_i(t), \tag{5}$$

where $\sigma_{^{137}\mathrm{Cs}}(t)$ is the ground deposition of ^{137}Cs (kBq m^{-2}); $R_i(t)$ is the ratio of the activities of radionuclide i and of ^{137}Cs in ground deposition at time t, unitless.

The estimation of the variation with time of the deposition density of ^{95}Nb, ^{132}I and ^{140}La takes into account the deposition of their precursors ^{95}Zr, ^{132}Te and ^{140}Ba, respectively:

$$\sigma_i(t) = \sigma_i \cdot \mathrm{e}^{-\lambda_{\mathrm{r}}^i \cdot t} + \sigma_{p,i} \cdot f_i \cdot \frac{\lambda_{\mathrm{r}}^i}{\lambda_{\mathrm{r}}^i - \lambda_{\mathrm{r}}^{p,i}} \cdot \left(\mathrm{e}^{-\lambda_{\mathrm{r}}^{p,i} \cdot t} - \mathrm{e}^{-\lambda_{\mathrm{r}}^i \cdot t}\right), \tag{6}$$

where σ_i and $\sigma_{p,i}$ are the initial deposition densities of radionuclide i and of its parent, respectively (kBq m^{-2}); λ_{r}^i and $\lambda_{\mathrm{r}}^{p,i}$ are the radioactive decay constants of radionuclide i and of its parent, respectively (d^{-1}).

The attenuation function, $r(t)$, that reflects the decreasing dose rate with time due to the migration of the deposited activity to deeper layers of soil was taken to be[18]:

$$r(t) = p_1 \cdot \mathrm{e}^{-\lambda_1 \cdot t} + p_2 \cdot \mathrm{e}^{-\lambda_2 \cdot t}, \tag{7}$$

where $p_1 = 0.49$, $p_2 = 0.51$, $\lambda_1 = 7.91 \times 10^{-4}$ d^{-1} and $\lambda_2 = 5.1 \times 10^{-5}$ d^{-1}.

The values of the conversion factors from plane source on ground surface to effective dose to adults were taken from Ref. (8). To account for the effect of the soil-roughness and the initial penetration of radionuclides into the soil, a reduction factor of 0.82 was used[11].

The behavioural factors, $\mathrm{BF_r}$ and $\mathrm{BF_u}$, were taken to be 0.36 and 0.18 for the rural and the urban populations, respectively, for the estimation of the doses delivered in 1986; for the estimation of the doses delivered in the following years, the values of $\mathrm{BF_r}$ and $\mathrm{BF_u}$, were taken to be 0.31 and 0.16, respectively[1,5,17].

RESULTS AND DISCUSSION

Country-wide average doses were estimated for each of 40 countries in Europe. In addition, doses were estimated for each of the most contaminated regions of Belarus, Russia and Ukraine. Age-dependent thyroid doses from the intake of ^{131}I via inhalation and ingestion during the first 2 months after the accident (when practically all of the dose from the intake of ^{131}I was received) were estimated. Average effective doses due to external irradiation from radionuclides deposited on the ground surface and from the intake of long-lived radionuclides, notably ^{134}Cs and ^{137}Cs, were also estimated for the periods 1986, 1986–2005 and 1986–2065.

The geographical pattern of doses to the thyroid resulting from the intake of ^{131}I is shown in Figure 2 for children aged 1 y at the time of the accident. The highest average thyroid doses were received in the Gomel region of Belarus (750 and 150 mGy) for young children and for adults, respectively), in the Bryansk region of the Russian Federation (210 and 25 mGy, respectively) and in the Zhytomir region in Ukraine (170 and 40 mGy, respectively). Doses to infants were consistently higher than doses received by adults (see Table 3).

Thyroid dose resulted primary from the ingestion of ^{131}I with milk and leafy vegetables. Contribution of that exposure pathway varied on dietary habits of population of different ages and in general was responsible for up to 80–95% of the total dose.

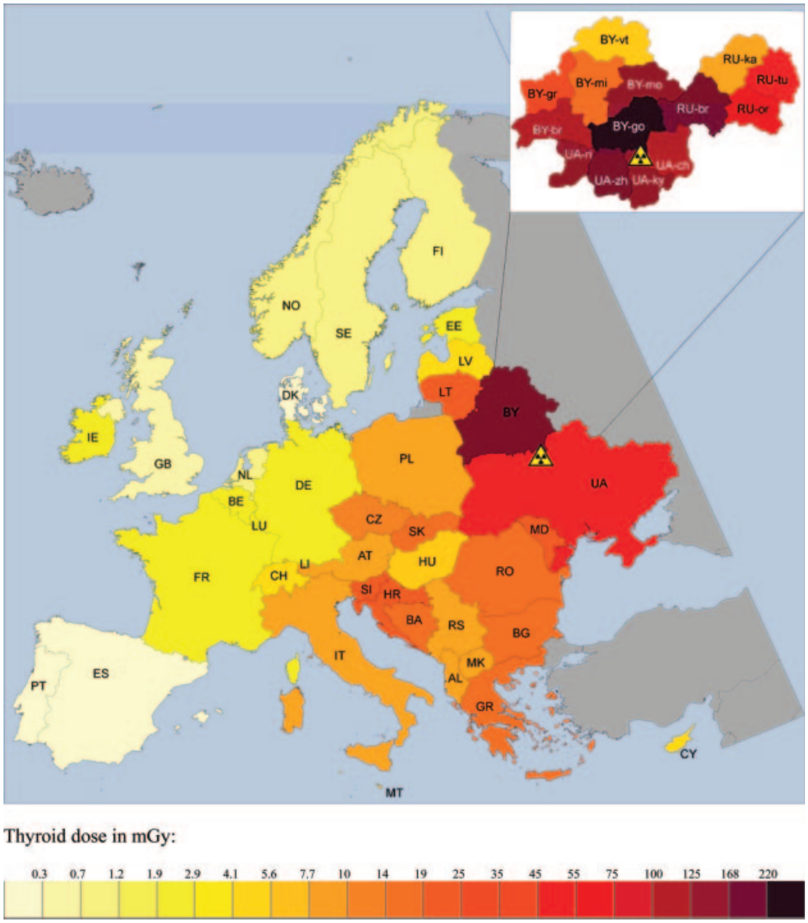

Figure 2. Spatial distribution of average country-specific thyroid doses from Chernobyl in Europe to children aged 1 y at the time of the accident. The radioactivity symbol denotes the location of the Chernobyl NPP. Names of countries are abbreviations according to ISO. For Belarus, Russian Federation and Ukraine the spatial distribution of doses is also given by Oblast. The following abbreviations were used for Oblasts. Belarus: for Brest, BY-br; for Gomel, BY-go; for Grodno, BY-gr; for Minsk, BY-mi; for Mogilev, BY-mo; for Vitebsk, BY-vt. Russia: for Bryansk, RU-br; for Kaluga, RU-ka; for Orel, RU-or; for Tula, RU-tu. Ukraine: for Chernihiv, UA-ch; for Kyiv, UA-ky; for Rivno, UA-ri; for Zhytomir, UA-zh.

In countries where countermeasures were applied shortly after the accident to reduce the intake of radionuclides with locally produced foodstuffs as well in the northern Europe the inhalation pathway contributed up to 50% of the total thyroid dose from the intake of ^{131}I.

Average country-specific effective doses due to internal and external exposures from long-lived radionuclides are given in Table 3 for 1986 and for the 1986–2005 time periods. The spatial distribution of average country-specific effective doses accrued from 1986 to 2005 is shown in Figure 3. For the year 1986, effective doses were highest in Belarus and Ukraine, with average levels exceeding 0.5 mSv. Effective doses of the same order were also delivered in the most contaminated regions of Russia. In 1986–2005, the average effective doses were 2.8 mSv in Belarus, 5.1 mSv in the contaminated areas of Russia and 2.1 mSv in Ukraine. In other countries, effective doses greater than, or about equal to, 1.0 mSv were found for Finland, Austria, Moldova and Slovenia. Doses in the period 1986–2005 represent, on average, ~85% of the lifetime dose from Chernobyl that would be accumulated by a person who lived until the year 2065.

For Europe as a whole, average effective dose in 1987 was half that of 1986. By 2005, the annual average dose was <5% of that in 1986. The average effective doses for the 1986–2005 time period in the Gomel region of Belarus and in the Bryansk region

Table 3. Country/region-specific dose estimates.

Country	Thyroid dose from the intake of ^{131}I (mGy) for age group		Whole-body effective dose (mSv) accrued in the period	
	1 y	Adults	1986	1986–2005
Albania	9.4	2.8	0.16	0.52
Austria	8.5	0.9	0.37	0.98
Belarus, Brest Oblast[22]	123	26	0.62	2.3
Belarus, Vitebsk Oblast[22]	7.0	2.0	0.05	0.12
Belarus, Gomel Oblast[22,70]	750	153	3.4	9.7
Belarus, Grodno Oblast[22]	28	5.8	0.32	0.85
Belarus, Minsk Oblast[22]	16.3	4.7	0.26	0.68
Belarus, Minsk-City[22]	100	18	0.17	0.68
Belarus, Mogilev Oblast[22]	128	31	1.5	4.4
Belgium	2.1	0.4	0.01	0.03
Bosnia and Herzegovina	18.4	5.7	0.12	0.41
Bulgaria[30]	16.6	3.1	0.25	0.64
Croatia	21.4	5.0	0.19	0.47
Cyprus	4.6	1.1	0.03	0.08
Czech Republic[34]	11.7	1.7	0.09	0.37
Denmark	0.1	0.02	0.01	0.03
Estonia	2.4	0.7	0.05	0.14
Finland[36,71]	1.1	0.3	0.21	1.36
France	2.1	0.3	0.03	0.07
Germany	2.2	0.3	0.06	0.17
Greece	17.8	2.0	0.33	0.72
Hungary	5.7	0.7	0.11	0.3
Iceland[a]	-	-	0.001	0.01
Ireland	2.3	0.4	0.07	0.21
Italy	8.2	1.2	0.15	0.33
Latvia	5.1	1.5	0.04	0.10
Liechtenstein	8.9	0.9	0.28	0.91
Lithuania[44,59]	22.7	4.3	0.16	0.33
Luxembourg	2.5	0.4	0.04	0.11
Macedonia	9.4	2.8	0.14	0.47
Malta	7.6	0.7	0.13	0.29
Moldova	20.3	3.9	0.36	0.97
Netherlands	0.9	0.3	0.02	0.05
Norway	0.9	0.2	0.16	0.38
Poland	7.8	0.8	0.11	0.25
Portugal	0.008	0.002	0.001	0.003
Romania	17.2	2.0	0.23	0.61
Russia, Bryansk Oblast[20,72,73]	210	26	3.2	10.9
Russia, Kaluga Oblast[16,20,73]	10	2	0.63	1.7
Russia, Orel Oblast[16,20,73]	60	10	1.2	2.8
Russia, Tula Oblast[16,20,73]	55	7	1.4	3.4
Serbia and Montenegro	9.3	2.8	0.16	0.55
Slovakia	17.3	2.1	0.16	0.41
Slovenia	20.4	6.3	0.30	0.98
Spain	0.1	0.02	0.004	0.009
Sweden	0.9	0.2	0.12	0.31
Switzerland[51]	3.5	2.0	0.17	0.46
Ukraine, Chernihiv Oblast[14,70]	120	24	0.5	1.7
Ukraine, Kyiv Oblast[14,70]	166	33	1.4	3.9
Ukraine, Kyiv-City[14,70]	72	12	0.45	1.3
Ukraine, Rivno Oblast[14]	146	29	1.0	5.6
Ukraine, Zhytomir Oblast[14,70]	170	38	1.6	5.7
Ukraine, remainder[14]	28	5.4	0.57	1.9
United Kingdom	0.7	0.08	0.02	0.05

[a]External dose only from deposition of $^{134,137}Cs$ was estimated

of Russia were estimated to be ~20 times higher (~10 mSv) than those for Europe as a whole (0.5 mSv).

Contributions of caesium ingestion and external exposure to the average effective dose accrued in the period 1986–2005 (with very small contribution of inhalation of caesium) varied between countries depending on the radionuclides mixture in deposition, the transfer of radionuclides to foodstuffs, dietary habits of population, implementation of countermeasures, etc. For the entire Europe, almost half (54%) of effective dose was formed by the intake of $^{134,137}Cs$ with foodstuffs while external exposure accounts for 46%.

Comparison with UNSCEAR 1988 Report

Doses estimated in this paper were compared with doses published in the UNSCEAR 1988 Report[5]. The comparison was limited to the countries of Northern, Central and Western Europe. Former states of the USSR (Estonia, Latvia, Lithuania, Moldova), Albania and Liechtenstein were not included in the comparison as doses for these countries were not estimated in the UNSCEAR 1988 Report[5]. In addition, the comparison did not include the republics of the former Yugoslavia (Bosnia and Herzegovina, Croatia, Macedonia, Serbia and Montenegro, Slovenia), the Czech Republic, four contaminated Oblasts in Russia, Slovakia and Ukraine as the doses published in the UNSCEAR 1988 Report[5] were for specific sub-regions that did not cover the entire territory of these countries.

Figure 4 shows the ratios of thyroid doses from the intake of ^{131}I for infants estimated in this paper to those contained in the UNSCEAR 1988 Report[5]. As can be seen from the figure, there is good agreement between the two estimates for the majority of countries. This is not surprising, as the same input data were used for dose reconstruction in these countries and only the dose coefficients[6,7] used in current estimates reflect a difference between the two approaches. For other countries, Belarus, Bulgaria, Finland, Italy and Switzerland, the difference between the two sets of doses is more significant. In particular, thyroid doses estimated for Belarus differ significantly from the doses in the UNSCEAR 1988 Report[5]. Current estimates are lower compared with previous estimates[5] by a factor of 2 for Switzerland, Finland, and Bulgaria. Thyroid doses for these countries were estimated taking into account countermeasures (Switzerland) or based on direct thyroid measurements (Bulgaria). On the other hand, current estimates of thyroid dose for Italy are ~2 times higher than previous estimates[5]. The thyroid dose calculated in this paper for Italy is nearly median between those doses estimated taking

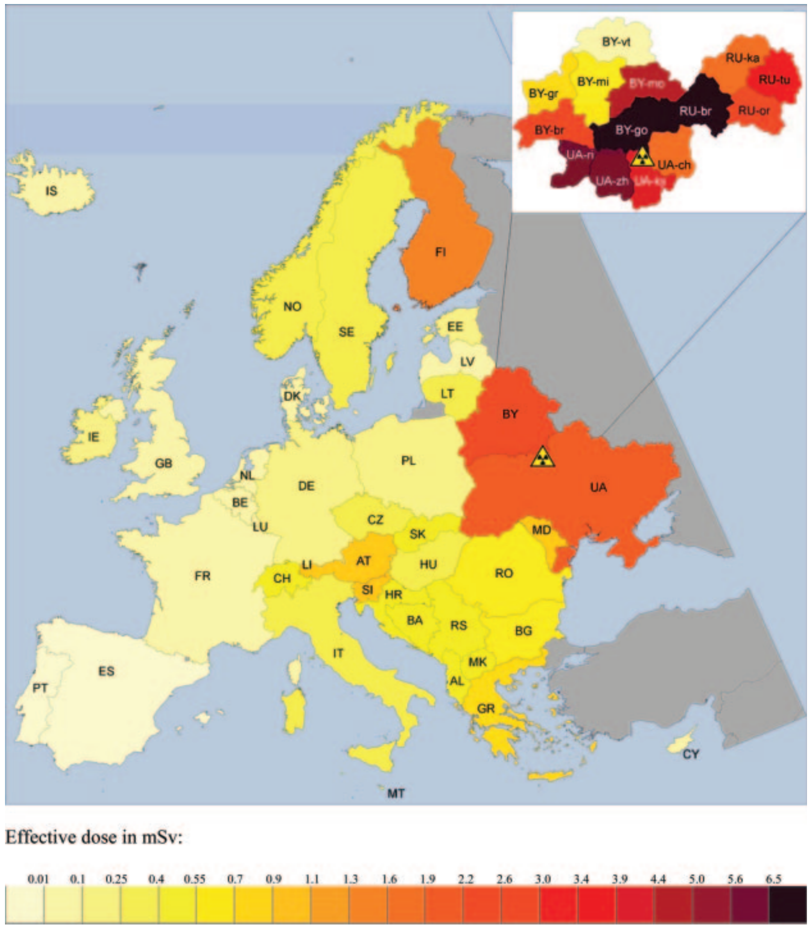

Figure 3. Spatial distribution of average country-specific effective doses from Chernobyl in Europe accrued in the period 1986–2005. Abbreviations are the same as in Figure 2.

countermeasures into account, and those estimates without adjusting for countermeasures(4), while the doses evaluated in the UNSCEAR 1988 Report(5) are doses estimated taking countermeasures into account.

Figure 5 shows ratios of whole-body doses for adults: those estimated in this paper to those published in the UNSCEAR 1988 Report(5). The difference between the two sets of country-specific effective doses could be the result of the following factors:

(1) The difference in country-specific ^{137}Cs ground deposition densities used for dose reconstruction. As mentioned above, the deposition densities of ^{137}Cs from Chernobyl fallout contained in the Atlas(2) were used in this paper. It might be expected, that deposition data from a comprehensive monitoring programme(2) would be different from those published in 1988, which was information obtained in a rather short period after the accident. Indeed, population-weighted deposition densities of ^{137}Cs derived from the Atlas(2) and given in the UNSCEAR 1988 Report(5) are, respectively, 0.3 and 0.8 kBq m^{-2} in Belgium, 0.3 and 1.8 kBq m^{-2} in The Netherlands, 2.8 and 4.7 kBq m^{-2} in Germany, 6.5 and 9.7 kBq m^{-2} in Romania, 0.36 and 1.3 kBq m^{-2} in Denmark, 1.3 and 5.2 kBq m^{-2} in Poland, 1.2 and 2.7 kBq m^{-2} in Luxembourg, etc. The latest estimates of ^{137}Cs ground deposition densities in a majority of the European countries considered are lower than those reported in the UNSCEAR 1988 Report(5). On the other hand, deposition densities of ^{137}Cs are, respectively, 0.06(2) and 0.03(5) kBq m^{-2} in Spain. As ^{137}Cs ground deposition density is one of the main input parameter for the estimation of external dose, difference in deposition used for dose calculation led to difference in dose estimates.

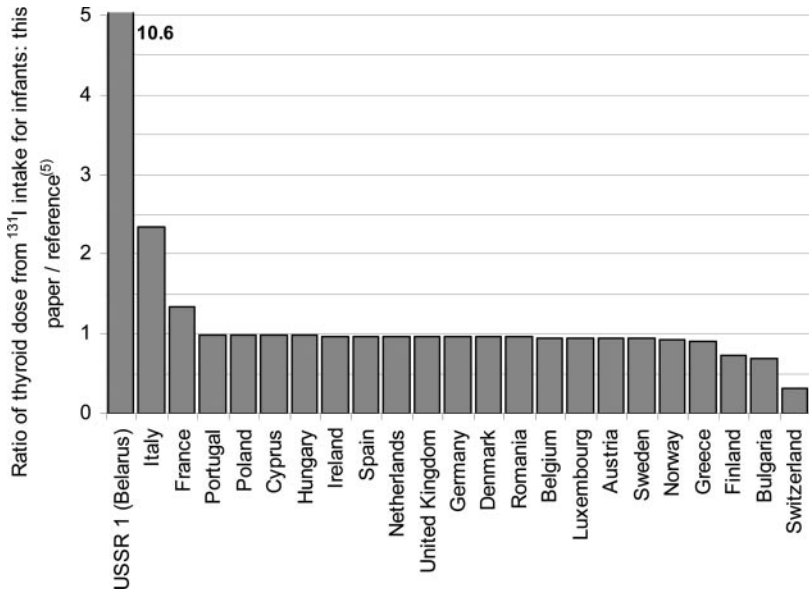

Figure 4. Ratios of thyroid doses from the intake of ^{131}I for infants: estimated in this paper to given in UNSCEAR 1988 Report[5].

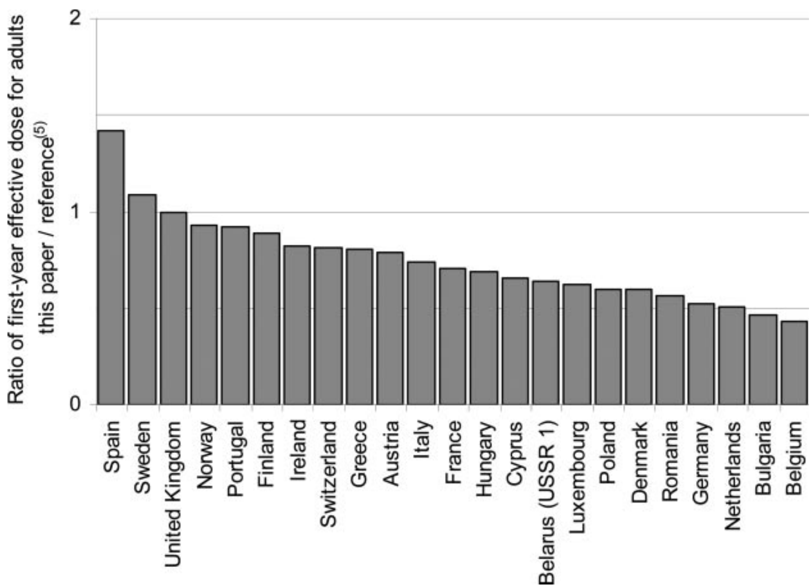

Figure 5. Ratios of effective dose for adults: estimated in this paper to given in UNSCEAR 1988 Report[5].

(2) This paper considers exposure due to inhalation of ^{134}Cs and ^{137}Cs only, while inhalation dose from the intake of a mixture of radionuclides was provided in the UNSCEAR 1988 Report[5]. However, inhalation dose is rather small compared with dose from caesium ingestion and external exposure.

Uncertainties in dose estimates

Within a specific settlement or age group, the individual doses show a significant variability. Uncertainty factors of average doses over the settlement might vary in the range 1.6–2.4 for thyroid doses from the intake of ^{131}I[74,75] and 1.2–1.5 for external doses from radionuclides deposited on the ground[18,76,77]. Sources of uncertainties are fluctuations in the radionuclides concentration in foodstuffs produced at the same location, as well as difference in behaviours and dietary habits from one individual to another, and inter-person variability in the metabolic parameter values. These uncertainties are important when individuals are considered.

However, they are smoothed out to great extent when average dose over the population of a large region is estimated, and the uncertainty of average doses over the population of a country is much lower. This uncertainty associated with the spatial variation of the radionuclides concentration in air, soil and in foodstuffs. The regional average concentration may differ significantly from the result obtained in a few measurement points in the region. Variability in dietary habits between regions of country is also source of uncertainty. In this paper uncertainties in doses were subjectively estimated based on the availability and reliability of radiation data used for dose reconstruction for each particular country. While errors in mean population doses were assumed to be smallest in the most contaminated countries (Belarus, Ukraine and the Russian Federation) where comprehensive dose reconstruction has been done on the basis of results of intensive radiation monitoring, higher uncertainties were assigned to dose estimates obtained from very limited data (Albania, Bosnia and Herzegovina, Iceland, Macedonia).

Assuming that the estimated doses are log–normally distributed, the geometric standard deviation of the distribution of the average thyroid dose estimates was evaluated to range from 1.2 in the most contaminated areas, where they were based on direct thyroid measurements (Gomel region in Belarus, Bryansk region in Russia, and Kiev and Zhytomir regions in Ukraine) to 2.0 in the least contaminated countries. The geometric standard deviation of the average effective dose estimates ranged from 1.1 in the most contaminated areas (Belarus, the most contaminated regions of Russia, and Ukraine) to 1.6 in the least contaminated countries.

Although this study focuses on the evaluation of average for country doses, it is obvious that there was variation in exposure levels between different regions of countries as well as between individuals. This variation of doses is not caused only by the difference in ^{137}Cs deposition but also by different nutritional habits and by the countermeasures. A number of countries took measures to reduce the population exposure to fallout from the Chernobyl accident. The most effective of these measures were the prohibition on feeding lactating cows with fresh grass and the recommendation to avoid consuming fresh milk and leafy vegetables. These measures, when taken during the few first weeks after the accident, resulted in a substantial reduction of the doses, especially in the thyroid doses to children[27,51]. Later, countermeasures were also effective in reducing internal exposure from radiocaesium ingestion[12,46,78,79].

CONCLUSIONS

On the occasion of the 20th anniversary of the Chernobyl accident an attempt has been made to evaluate the impact of the Chernobyl accident on the global burden of human cancer in Europe. For this, country-wide average doses were estimated for 40 countries in Europe; in addition, doses were estimated for each of the most contaminated regions of Belarus, Russia and Ukraine. Age-dependent thyroid doses from the intake of ^{131}I via inhalation and ingestion during the first 2 months after the accident (when practically all of the dose from the intake of ^{131}I was received) were estimated. Average effective doses due to external irradiation from radionuclides deposited on the ground surface and from the intake of long-lived radionuclides, notably ^{134}Cs and ^{137}Cs, were also reconstructed for the periods 1986, 1986–2005 and 1986–2065.

Dose estimates are based on the analysis and compilation of data either provided by experts from Belarus, Bulgaria, Croatia, the Czech Republic, Finland, Lithuania, the Russian Federation, Switzerland and Ukraine or published in the scientific literature for those and other countries in Europe. The average individual doses to the thyroid from the intake of ^{131}I for children aged 1 y were found to vary from 0.008 mGy in Portugal up to 750 mGy in Gomel Oblast (Belarus). The average individual effective doses from external exposure and ingestion of long-lived radiocaesium accrued in the period 1986–2005 varied from almost zero in Portugal to ~10 mSv in Gomel Oblast (Belarus) and Bryansk Oblast (Russia). The average individual effective dose from the Chernobyl fallout for the 1986–2005 time periods for Europe as a whole was estimated to be ~0.5 mSv. In comparison, the average effective dose from natural background radiation, excluding radon, over the same 20 y was of the order of 20 mSv.

This study focuses on the evaluation of average for country doses. Therefore, doses are associated with uncertainties arising from the following main sources: heterogeneity and spatial variation observed within regions in the radionuclides concentration in air, soil and in foodstuffs; and uncertainties in sampling which may lead to the fact that the regional average concentration may differ from the result obtained in a few measurement points in the region (especially, in less contaminated countries). It should be noted that more radiation data that were not taken into account in this paper might be available for some countries and might improve the results and lower uncertainties in exposure assessment to the population of Europe.

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