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External and Internal Irradiation of a Rural Bryansk (Russia) Population from 1990 to 2000, following High Deposition of Radioactive Caesium from the Chernobyl Accident

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Abstract

In 1990, a joint Nordic-Russian project was initiated in order to make independent estimations of the effective dose to selected groups of inhabitants in a highly contaminated area around the city of Novozybkov in the western Bryansk region of Russia. The inhabitants were living in six villages with initial contamination levels of ^{137}*Cs between 0.9 and 2.7 MBq* m^{-2}*. Some villages had been decontaminated, others not. Both school children and adults participated in the study. The external irradiation of 100-130 inhabitants was determined during one month in September-October each year from 1990 to 2000 (except 1999), using individual thermoluminescent (TL) dosemeters. The body burden of* ^{137,134}*Cs was determined by in vivo measurements in about 500 inhabitants annually from 1991 to 2000, and for a subgroup also with analysis of the* ^{137}*Cs concentration in urine. The mean effective dose (E) from external and internal irradiation due to* ^{137,134}*Cs deposition varied between 2.5 and 1.2 mSv per year between 1990 and 2000. The total mean E decreased, on average, by 9% per year, while the mean external dose decreased by 16% per year. The dose rate from internal radiation decreased more slowly than the dose rate from external radiation, and also showed an irregular time variation. The contribution from the internal dose to the total E was 30-50%, depending on the village. Predictions for the long-term changes in the effective dose to people living in the areas are presented. The cumulated E for the 70-years following the accident was estimated to about 90 mSv with the assumption that both internal and external dose decrease by 2% per year after year 2000. The highest E during a life-time received by single individuals living in the area may amount to around 500 mSv considering the individual variations in E.*

Introduction

The Chernobyl nuclear power plant accident in 1986 led to a high level of radioactive contamination in the Bryansk area in southwest Russia, some 150-250 km north-northeast of the nuclear power plant. An area of approximately 2,400 km^2, having a population of about 112,000, was contaminated with ^{137}Cs and ^{134}Cs, resulting in a deposition of ^{137}Cs per unit area of more than 0.55 MBq m^{-2}. These areas were designated "controlled areas" (CA) by the Soviet authorities (1). During the years after the accident countermeasures, such as relocation of inhabitants (in 1986 and in 1990), provision of uncontaminated food (beginning from August, 1986), and decontamination of a number of villages (1989), were undertaken in certain areas. Since the time of the accident, people living in the contaminated areas have been exposed to both external and internal radiation, mainly from ^{137}Cs. In 1990, a joint Nordic-Russian programme was established to assess the effective doses to individuals in a number of villages in a western district of the Bryansk area around the town of Novozybkov. Yearly expeditions were carried out between 1990 and 1998 and in 2000. The long-term changes in both internal and external irradiation were investigated as well as different methods of estimating the internal and external effective dose (2, 3, 4, 5, 6).

The aim of this work was to further analyse the irradiation, in terms of the effective dose (E) to the inhabitants of the villages from external as well as internal radiation from ^{137}Cs and ^{134}Cs. Moreover, the relation between internal and external E from 1986 to 2056 was estimated, employing the results of our own measurements and published data. A comparison was also made between the body burden of ^{137}Cs estimated from *in vivo* measurements and that calculated from urine samples. Mean values of the annual external and internal E are presented for each village.

Material and methods

Location and participants

The villages in the study, with reported ^{137}Cs depositions of between 0.9 and 2.7 MBq m^{-2} (7), are situated in a rural area near the town of Novozybkov, in the south-western part of Russia. Each village has a population of 300-600 inhabitants, whose principal occupation is agriculture on state-owned or private farms. Measurements were performed in September or October each year from 1990 to 2000, with the exception of 1999. The volunteers were between 2 and 80 years old and lived in either brick or wooden houses. A large proportion of the participants were school children.

Due to rainfall when the radioactive cloud from Chernobyl passed over the area, the deposition was high and its pattern very inhomogeneous. This means that the deposition can vary by an order of magnitude, even within small areas. Various types of countermeasures were applied shortly after the accident, and the villages were decontaminated to various extents in 1989. This was usually done by removing the topsoil around kindergartens, schools and other public places as well as along the roads, and then covering the ground with gravel or asphalt.

Assessment of body burden of caesium radionuclides

Estimations of the body burden of ^{137}Cs and ^{134}Cs were carried out by *in vivo* measurements on the inhabitants from five villages with the additional collection of urine samples from a sub-group of the adult individuals. Estimations of the body burden of ^{137}Cs in inhabitants from the various villages by means of urine samples were performed yearly between 1991 and 1998 (8, 9, 10). Single urine samples (20-100 mL) were collected from around 50 individuals at the time of the whole-body measurements. A few milligrams of stable CsCl and approximately 1.0 mL concentrated (12 M) HCl per 100 mL of urine were added to the samples within 24 hours in order to prevent adhesion of radioactive Cs on the container walls. A number of samples were analysed by means of gamma spectrometry at The Branch of Institute of Radiation Hygiene in Novozybkov, Russia, using a scintillation spectrometer (SGS-200) before being transported to Sweden. The concentration of ^{137}Cs was then measured at the Department of Radiation Physics either in Malmö (HPGe, 35% relative efficiency at 1.33 MeV) or in Göteborg (125 mm (∅) × 100 mm NaI(Tl)). The statistical uncertainty (1 SD) in the urine ^{137}Cs measurements was estimated to less than 5% for all detector systems. Potassium and creatinine were also analysed within two weeks of sampling (9, 10). A comparison of the results between the Swedish and the Russian laboratories showed a difference of less than 10% in the mean values of caesium concentration in the urine samples.

The calculation of the body burden of ^{137}Cs from the concentration of ^{137}Cs in single urine samples, was performed using published data reviewed by Rääf (11), on the ratio of whole-body ^{137}Cs to the daily urinary excretion (167 and 119 Bq/Bq d^{-1} - for men and women, respectively), and assuming a daily urine volume of 1.4 L for men and 1.1 L for women (12). In a previous study (10) we found that normalisation of the urinary excretion to various parameters such as potassium and creatinine did not improve the calculations of the ^{137}Cs body burden, thus, we did not introduce normalisation into the present calculations.

A NaI(Tl) detector (63 mm (∅) × 63 mm) and a single-channel scintillation spectrometer (RFT-20046, Robotron, Germany) were used to perform direct *in vivo* determination of the ^{137,134}Cs body burden in about 500 inhabitants yearly from 1991 to 2000 (3, 6, 13). The measurements were usually conducted in school buildings with brick walls, with comparatively favourable measuring conditions in terms of signal-to-background ratio. They were carried out with the individual in a sitting position, bending over the detector which was resting in the lap directed towards the abdomen (13, 14). The measurement time was 60-100 s. The calibration method for ^{137}Cs and ^{134}Cs measurements *in vivo* was developed in a study with volunteers who ingested known amounts of the radionuclides, and verified with measurements of the same persons in a well-shielded, stationary whole-body counter (15). The energy interval used for the measurements in the period 1990-1994 was 500 to 1000 keV, thus including gamma radiation from both ^{137}Cs (662 keV) and ^{134}Cs (main peaks from 563 to 802 keV). After 1994, the activity of ^{134}Cs was negligible compared with that of ^{137}Cs. Before and after each series of measurements, the background count rate was measured in the absence of the person under investigation. For a normal background (close to natural levels), the minimum detectable body burden was estimated to be 1-2 kBq. The coefficient of variation (CV) at that level was estimated to be 50%, and at a body burden of 10 kBq it was estimated to be 20%. A more detailed description of the calibration and calculation methods is given elsewhere (13, 15).

Measurements of external irradiation

In six villages thermoluminescent (TL) dosemeters, consisting of 3x3x0.9 mm^3 Lithium Fluoride (LiF) chips (Harshaw TLD 100), were used to assess the absorbed dose to individuals from external irradiation in their environment. During 1990-1992, Calcium Fluoride (CaF_2) dosemeters from the Norwegian Radiation Protection Authority and LiF dosemeters from the Institute of Radiation Hygiene, St Petersburg, were used in parallel, (details can be found elsewhere, (2)). From 1993 and onwards, only Swedish dosemeters were used. These were prepared and evaluated in Malmö or Göteborg, Sweden, and calibrated in the beam of a ^{60}Co reference source. The calibration was traceable to the secondary standard dosimetry laboratory at the Swedish Radiation Protection Authority (SSI). The dosemeters were transported to Russia in a lead container with 10 mm thick walls, together with reference dosemeters which were stored in the container during the whole process in order to estimate the background signal accumulated during travelling and storage. The LiF chips were mounted in a polyethylene dosemeter holder and worn by the participants on a chord around the neck for a period of one month in September or October. Upon collection from the participants, the dosemeters were put back into the lead container and sent to Sweden for evaluation. A more detailed description of the TL- measurements has been published earlier (16).

Calculation of effective dose

The annual effective dose from internal exposure, E_{int}, was calculated using the measurements of the body content of ^{137}Cs and ^{134}Cs and the age-dependent metabolic and dosimetric parameters for caesium radionuclides obtained from ICRP publications 56 and 67 (17, 18). The annual effective dose for an individual was calculated according to the equation:

$$E_{int} = r_{sum}(m) \cdot A/m \qquad mSv \qquad (Eq.\ 1)$$

where r_{sum} is the dose rate coefficient (mSv/y per kBq/kg) for the total content of ^{137}Cs and ^{134}Cs in a person with body mass m (kg), as presented in (3), but recalculated using updated dose coefficients from ICRP publication 67 (18). In r_{sum} corrections were made for the changing relative distribution of ^{134}Cs and ^{137}Cs between different years. The dose rate coefficients for people of different body masses were estimated from values of the committed effective dose per unit intake at a certain age (17). A is the measured sum of the activities of ^{137}Cs and ^{134}Cs in the body (kBq). The calculated effective dose values were compared with those obtained using annual effective dose factors for adults (70 kg) of 35µSv kBq^{-1} and 50 µSv kBq^{-1} for ^{137}Cs and ^{134}Cs, respectively (19, 20) and were found to agree well, within 15%. The yearly E may be somewhat overestimated, since our measurements were carried out in the autumn, when the body burden of ^{137}Cs has been reported to sometimes be 60%-100% higher than during the spring and summer, mainly due to an increased intake of forest products in the summer and autumn (6, 21, 22).

The effective dose from external radiation, E_{ext}, was calculated according to the equation:

$$E_{ext} = D_{surface} \cdot (K_{air}/D_{surface}) \cdot (E/K_{air}) \qquad Sv \qquad (Eq.\ 2)$$

where $D_{surface}$ is the absorbed dose to the body surface, as measured with the dosemeter, K_{air} is the air kerma and E is the effective dose. For superficial activity deposition, most of the energy fluence at a height of 1 m is from photons with an angle of incidence only slightly below 90° with respect to the normal of the infinite plane air-soil interface (23). This means that, in this case, the irradiation geometry can be assumed to be “rotational invariant”. For adults (> 15 years), we used a product of the two conversion factors, $E/D_{surface}$, of 0.92 Sv/Gy (24, 25). For school children we multiplied the dosemeter reading by 0.95 Sv/Gy to obtain the effective dose (26). The same values were used during the whole study period. The uncertainty in the conversion factors has been estimated earlier to be 5%, expressed in terms of 1 SD (27). The value of the effective dose per month (September-October) was multiplied by 12 and by 0.94 (28) in order to obtain the annual E, corrected for snow cover during winter-time.

Results and discussion

Body burden of ^{137}Cs

The mean body burden of ^{137}Cs estimated from measurements on urine samples is given in Table 1, together with estimates from direct measurements of body burden. Considering the estimated uncertainty, the mean values agree. The results from the urine samples show a greater range (towards higher values) for most years, compared with the values measured *in vivo*. The larger spread in the data from urine samples may be caused by the variability in the ^{137}Cs concentration in the urine, as only single samples were collected, and a daily volume had to be estimated (1.4 L for men and 1.1 L for women). The process of calculating the body burden of ^{137}Cs from single urine samples involves large uncertainties, mainly due to the biological characteristics of different individuals that could cause errors of 50-90% in the calculated whole body burden (5). The uncertainty in the sampling and calibration procedures of urine samples is much less and estimated to be around 10-15% (1SD). However, this technique is applicable when estimating the mean body burden in a population.

Table 1. A comparison of the estimated mean values of the body burden of ^{137}Cs in adults, calculated from urine samples and from direct *in vivo* measurements in the same individuals. N is the number of individuals. The mean ± 1 SD of the mean is presented, together with the minimum and maximum values in parentheses.

	Body burden of ^{137}Cs (kBq)	
Year	**Method**	
	Urine samples	***In vivo* measurements**
1991 (N = 11)	55±22 (4-261)	48±14 (2-136)
1992 (N = 24)	25±4 (5-88)	23±3 (4-52)
1993 (N = 23)	62±11 (4-211)	67±16 (8-371)
1994 (N = 26)	45±8 (11-192)	28±3 (4-69)
1995 (N = 15)	35±5 (4-85)	32±4 (6-81)
1996 (N = 15)	25±8 (5-135)	24±3 (7-48)
1997 (N = 6)	20±7 (5-51)	19±8 (5-59)

Results from the assessment of E_{int} between 1990 and 1994 were published by Zvonova et al. (3). A more detailed information of the body burden during the years 1998 and 2000, is given in Figs 1 and 2. The distributions of the body burden of ^{137}Cs as measured *in vivo* in adults and children (2-15 years old) from four villages (St Bobovichi, Kusnetz, Yalovka, Demenka) are presented. The distributions have an almost log-normal shape, with similar distribution widths in the data for both years. The mean values of the body burden were, on average, higher in 1998 than in all the other years, probably due to a greater intake of mushrooms during 1998. For most years, children exhibited lower body burdens than adults, but the concentration of ^{137}Cs (per unit body weight) was not always significantly different between children and adults. However, in 1998 the mean activity concentrations of ^{137}Cs were significantly higher ($p<0.05$) in adults than in children (880 and 420 Bq kg^{-1}, respectively), possibly since adults consume relatively larger amounts of mushrooms during seasons with rich mushroom harvests, as the children eat some of their meals at school. The contribution to the daily intake of ^{137}Cs from forest products has increased with time, and may constitute as much as 60-70% of the intake (29), which implies an increased E_{int} of people who consume considerable amounts of forest produce.

Effective dose relative to the deposition of ^{137}Cs

In Table 2, the main results of the estimates of the annual effective dose, from internal as well as external radiation, are summarised for adults in five villages, and for the time period between 1990 to 1998. The yearly mean effective dose in various villages varied between 0.8 and 3.6 mSv during the period. To evaluate the effect of decontamination, the mean value of the estimated yearly effective dose in each village was divided by the deposition of ^{137}Cs in 1986, before decontamination measures were instigated. The ratio between the contribution to the effective dose from external radiation and the deposition, (E_{ext}/dep), was about a factor of 2.3 higher in the slightly decontaminated villages than in the fully decontaminated village of Yalovka, in 1991. The difference persisted, and in 1996 the figure was 1.9. In the last column of Table 2, the results for the external dose, corrected for the physical decay of ^{137}Cs and ^{134}Cs, is presented. It was assumed that the air kerma rate from ^{137}Cs was 1.0 pGy h^{-1} per Bq m^{-2} and from ^{134}Cs 2.5 pGy h^{-1} per Bq m^{-2} (2) with a ratio of total deposited ^{134}Cs to ^{137}Cs of 0.54 in April, 1986. A reduction in the external effective dose of between 4% and 15% per year could still be seen, which reflects the further migration of activity to deeper soil layers, as well as erosion and human activities in general.

Considering the effective dose per unit deposition from internal irradiation, the figures show a difference between the slightly decontaminated village of Kusnetz and Yalovka, but several reasons other than deposition and degree of decontamination may explain this difference. The internal dose varies in a more complex way than the external dose, and depends on a number of factors, such as transfer factors from soil to plants, the distance to the nearest forest, dietary habits and degree of self-sufficiency. For example, the transfer factor from soil to milk was found to be a factor of four higher in Kusnetz than in Yalovka (3). It may be expected that the internal dose in a longer perspective after the accident would be increasingly dependent on the deposition of ^{137}Cs, as people tend to forget about the protective measures and the economic situation forces them to rely more on locally produced food. However, we did not find a correlation between internal dose and deposition level in our data.

Table 2. Estimated mean values of yearly effective dose for adults. E_{ext} refers to the contribution from external exposure and E_{int} to that from internal exposure. E_{tot} is the sum of the internal and external effective doses. $E_{ext,corr}$ is the external effective dose corrected for decay to 1986, dep refers to the deposited activity of ^{137}Cs in 1986. SD indicates slightly decontaminated, PD partly decontaminated and FD fully decontaminated.

Village (MBq m^{-2} in 1986)	**Year**	**E_{ext}** mSv	**E_{int}** mSv	**E_{tot}** mSv	**E_{ext}/dep** mSv/MBq m^{-2}	**E_{int}/dep** mSv/MBq m^{-2}	**E_{tot}/dep** mSv/MBq m^{-2}	**E_{int}/E_{tot}**	**$E_{ext,corr}$/dep** mSv/MBq m^{-2}
Veprin	1991	2.0			2.2				4.5
(0.90, SD)	1992	1.8			2.0				4.5
	1993	1.5			1.7				4.1
	1994	1.2			1.3				3.3
	1995	1.1			1.2				3.2
	1996	1.1			1.2				3.4
	1997	1.0			1.1				3.2
	1998	1.0			1.1				3.3
Kusnetz	1991	2.0			2.1				4.3
(0.95, SD)	1992	1.9	1.2	3.1	2.0	1.3	3.3	0.39	4.5
	1993	1.5	2.1	3.6	1.6	2.2	3.8	0.58	3.8
	1994	1.5	1.2	2.7	1.6	1.3	2.8	0.44	4.1
	1995	1.3	1.1	2.4	1.4	1.2	2.5	0.46	3.7
	1996	1.0			1.1				3.1
	1997	0.8			0.8				2.3
	1998	0.6			0.6				1.8
St Bobovichi	1990	2.4			2.2				4.1
(1.1, PD)	1992	1.3	0.4	1.7	1.2	0.4	1.5	0.24	2.7
	1993	1.3	0.8	2.1	1.2	0.7	1.9	0.38	2.9
	1994	1.4	0.6	2.0	1.3	0.5	1.8	0.30	3.3
	1995		0.5			0.5			
	1996	0.9	0.4	1.3	0.8	0.4	1.2	0.31	2.2
	1997	0.3	0.5	0.8	0.3	0.5	0.7	0.63	0.9
	1998	0.5	1.5	2.0	0.5	1.4	1.8	0.75	1.5
St Vishkov	1990	1.8			1.4				2.6
(1.3, PD)	1993	1.3			1.0				2.4
	1994	1.1			0.8				2.0
	1995	0.8			0.6				1.6
	1996	1.2			0.9				2.5
	1998	0.8			0.6				1.8
Yalovka	1991	2.5			0.9				1.9
(2.7, FD)	1992	2.5	0.5	3.0	0.9	0.2	1.1	0.17	2.0
	1994	2	0.6	2.6	0.7	0.2	1.0	0.23	1.8
	1995	1.3	0.8	2.1	0.5	0.3	0.8	0.38	1.3
	1996	1.5	0.8	2.3	0.6	0.3	0.9	0.35	1.7
	1997		0.3			0.1			

Temporal trends and the annual effective dose from internal and external irradiation due to ^{137}Cs and ^{134}Cs

The effective dose from internal irradiation did not show any clear temporal trends during the period of the study. The activity concentration in milk has been found to decrease with a half-time of 10 years in the area (30, 31) in the remote period after the accident. Together with the fact that the activity concentration in forest products decreases essentially with the physical half-life of ^{137}Cs, the slow decrease in body burden is understandable, since the ^{137}Cs concentration in forest products is the parameter with the greatest influence on the body burden of ^{137}Cs today. In spite of the significant amounts of ^{137}Cs still coming from locally produced foodstuffs, the ingestion of natural forest products like mushrooms determine the main part of the body burden. In the years just after the accident the main source of ^{137}Cs intake was from contaminated milk (30, 32).

The mean annual effective dose from external and internal irradiation due to ^{137}Cs and ^{134}Cs for both children and adults varied between 1.2 and 2.5 mSv between 1991 and 2000, see Fig. 3. A pre-Chernobyl background of 45 µSv per month (16), was subtracted from E_{ext}. Although there is no such temporal trend in the internal effective dose level as for the external dose during this period, the total E from both internal and external radiation decreased with time, except in 1998. The total mean E decreased, on average, by 9% per year, while the mean E_{ext} decreased by 16% per year. Since the dose rate from internal exposure appeared to decrease more slowly than the dose rate from external radiation, its contribution to the total E from ^{137}Cs will become more important in the years to come. In 1991-1998 the contribution from E_{int} to E_{tot}, was between 17 and 75%, depending on the village, see Table 2. The average contributions from E_{int} and E_{ext} to E_{tot} are expected to be proportionally equal in this area between 2000 and 2056, for people not consuming forest products, while E_{int} could be expected to be a factor of 1.5-3 times higher than E_{ext} for people consuming significant amounts of these products (33).

During the first year after the accident, in May and June 1986, surface contamination of vegetation was the main source of intake of radionuclides via milk and leafy vegetables, thereafter the root pathway dominated (32). The average E_{int} from ^{137}Cs and ^{134}Cs to adult inhabitants of one village (St. Vishkov) in the controlled area (CA), calculated from measured body contents, during the first year (the first 365 days after the accident), was reported to be 3.2 mSv (1). During the second year, the dose decreased to 1.8 mSv, a reduction of 44%. Shutov et al. (32) reported that the ^{137,134}Cs content in the body decreased with a half-time of 1.25 years between 1986 and 1991, corresponding to an annual rate of decrease of 40% per year. By using these data for the period 1986 to 1991, the data presented here for the period 1991 to 2000 and assuming a further decrease of E_{int} after 2000 of 2% per year (due to the physical decay of ^{137}Cs) and 4% per year (realistic assumption), respectively, we calculated the cumulated internal doses for the 70-year period 1986 to 2056. The results are presented in Fig. 4. In the same figure, the cumulated external dose is also presented, calculated by using a conservatively assumed value of the reduction rate of 2% per year after 2000 and the reduction rate observed between 1991 and 2000 of 16%. A more likely rate of decrease for the external dose would be something in between 2% and 16%, and a value of 8% annual reduction rate, was also used, together with published data for the years prior to our measurements (34, 35). The sum of the cumulated external and internal doses for the three cases is also presented.

The cumulated mean effective dose during the 70-year period was estimated to be, on average, 90 mSv, assuming a reduction rate after 2000 of 2% per year for both internal and external irradiation. On the other hand, assuming a rate of decrease after 2000 of the internal and the external effective dose of 2% and 8% per year, respectively, results in 85 mSv. Assuming a more optimistic decrease rate of the effective dose where the external dose will decrease with the same rate as today (16%), together with a 4% reduction in the internal dose after 2000, the cumulated effective dose would be around 70 mSv. However, this is not a likely scenario, since the rate of decrease of the external irradiation is expected to slow down in the future, due to a slowing down in the downward migration of ^{137}Cs in the ground. Therefore the assumption of a rate of decrease of 8% per year during the years to come is more likely to occur. More than 50% of the effective dose was received before 2000, hence the assumptions made in the prognosis for the future have less influence on the cumulated effective dose. The cumulated effective dose from internal irradiation was estimated to 30-40 mSv. A prognosis of the internal effective dose between 1986 and 2056 for the same area was published by UNSCEAR (36). A figure of 32 mSv per unit area deposition of ^{137}Cs (MBq m^{-2}) in the CA is presented together with a prognosis for the external effective dose of 65 mSv per MBq m^{-2} in rural areas. According to our estimate single individuals in the Bryansk villages may receive a life-time effective dose of the order of 0.5 Sv.

Conclusions

The mean effective dose from external and internal irradiation due to ^{137}Cs and ^{134}Cs deposition on the ground to people in the studied villages in the Bryansk region varied between 1.2 and 2.5 mSv per year between 1990 and 2000. The total mean effective dose decreased, on average, 9% per year, while the mean external dose decreased by 16% per year. The dose rate from internal radiation decreased more slowly than the dose rate from external radiation. It also showed more variability in the values among various groups, as well as more variability from year to year compared to the external irradiation. The contribution from the internal dose to the total dose was between 17-75%, depending on village.

Considering only adults, the effective dose varied between 0.8 mSv and 3.6 mSv in the various villages during different years. A reduction in the effective dose from external radiation due to Chernobyl, of 4-15% per year, was found for the different villages after correction for the physical decay of ^{134}Cs and ^{137}Cs 1986, reflecting the migration of activity to deeper soil layers, as well as erosion and human activities.

The internal dose does not show the same regular time dependence as the external dose, and will contribute to a greater extent to the effective dose which will be received in the future. The effective dose from internal radiation varies in a more complex way than the effective dose from external radiation, and depends on a number of factors, such as transfer factors from soil to plants, the distance to the nearest forest, dietary habits and degree of self-sufficiency.

The effective dose due to external irradiation between 1991 and 2000, relative to the deposition of ^{137}Cs in 1986, was about a factor of 2 higher in the slightly decontaminated villages than in the fully decontaminated village, demonstrating the degree of efficiency of this protective measure.

The cumulated effective dose for the 70-year period following the accident was calculated to 90 mSv, with the conservative assumption that both internal and external dose decrease by only 2% per year.

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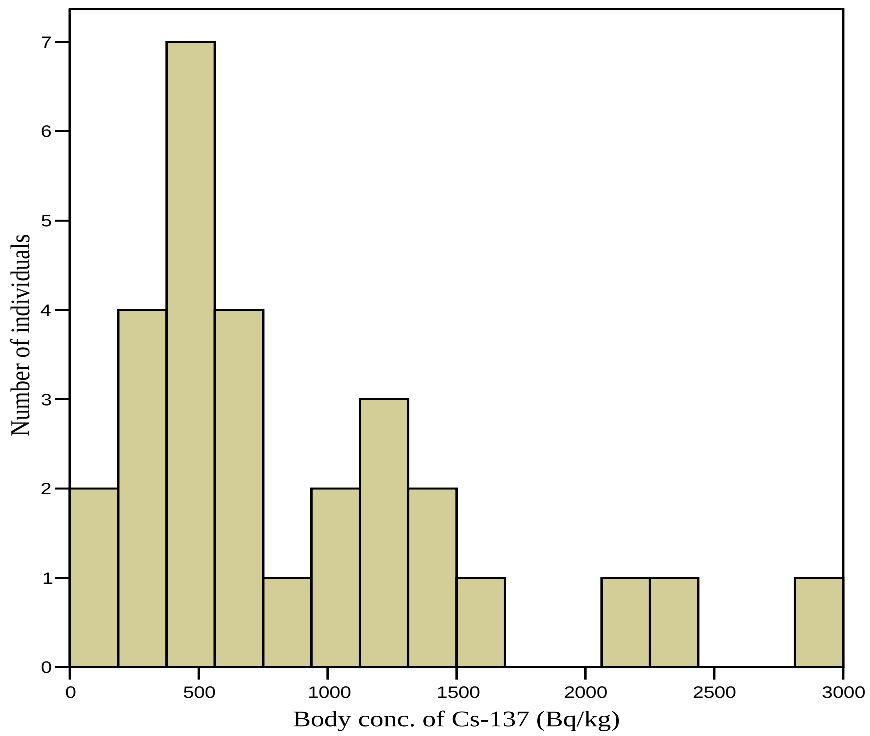

Fig. 1a. Distribution of the body concentration of ^{137}Cs in adults for the year 1998.

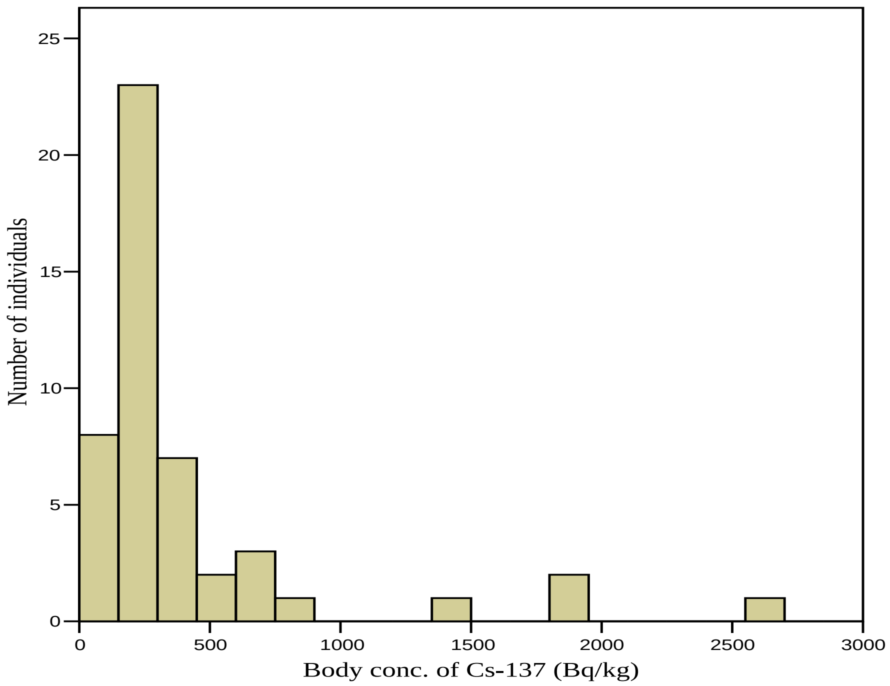

Fig. 1b. Distribution of the body concentration of ^{137}Cs in children for the year 1998.

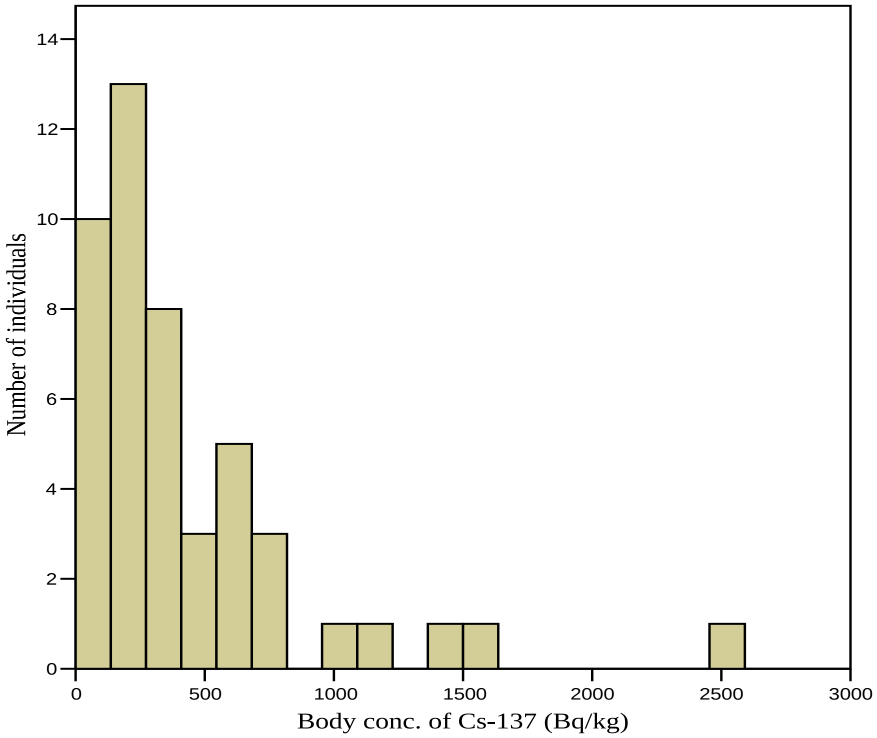

Fig. 2a. Distribution of the body concentration of ^{137}Cs in adults for the year 2000. (NB different scales in the x-axes.)

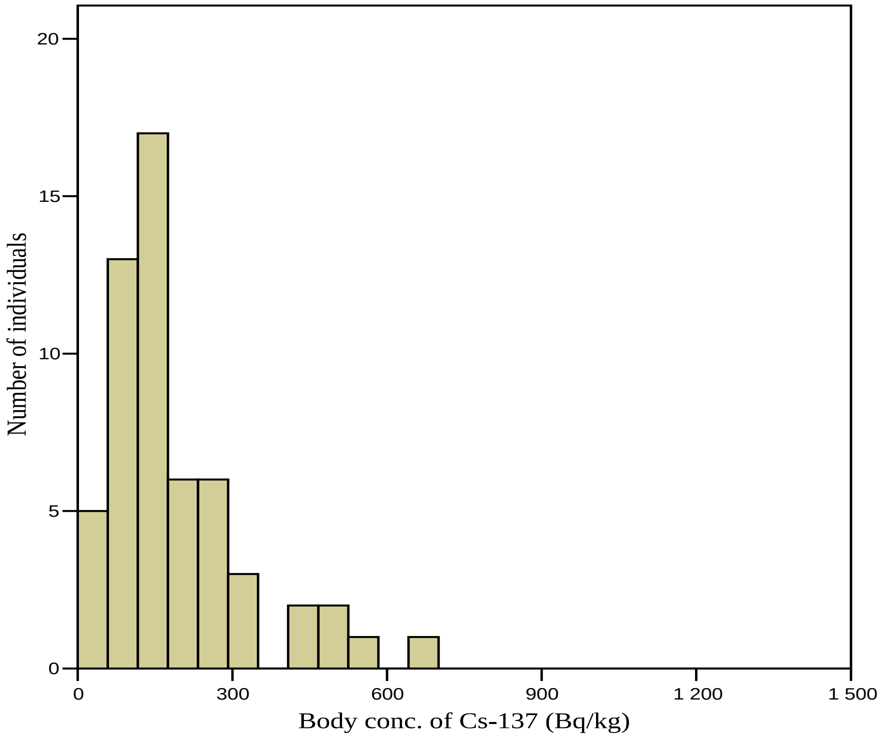

Fig. 2b. Distribution of the body concentration of ^{137}Cs in children for the year 2000. (NB different scales on the x-axis.)

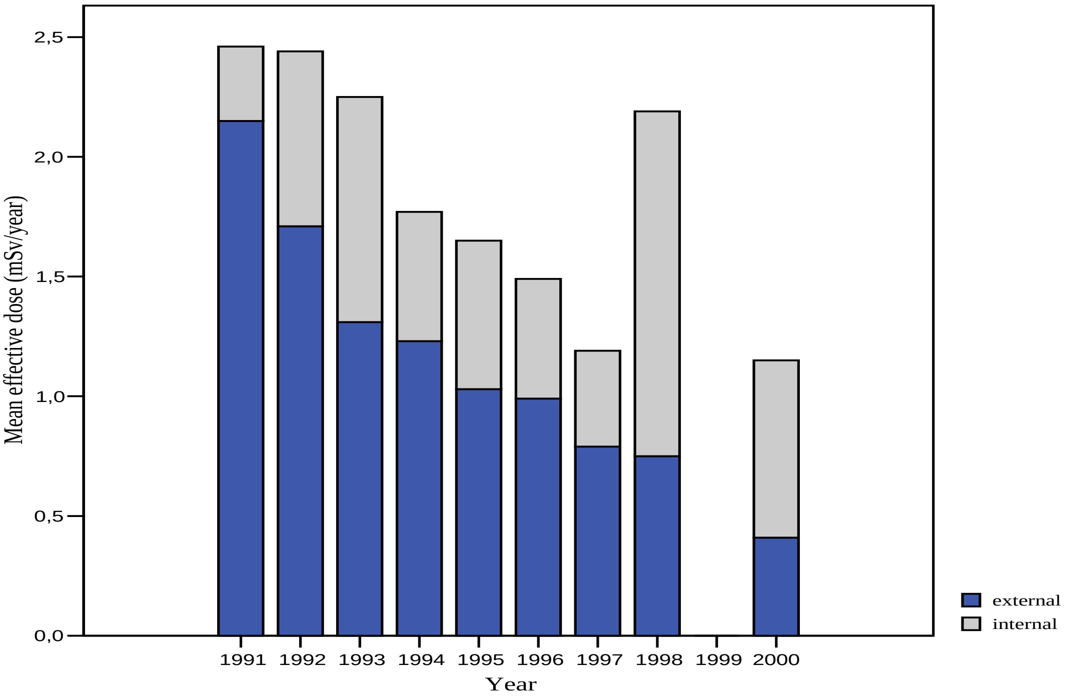

Fig. 3. Mean annual relative contributions from internal and external effective dose to adults and children from 1991 to 2000.

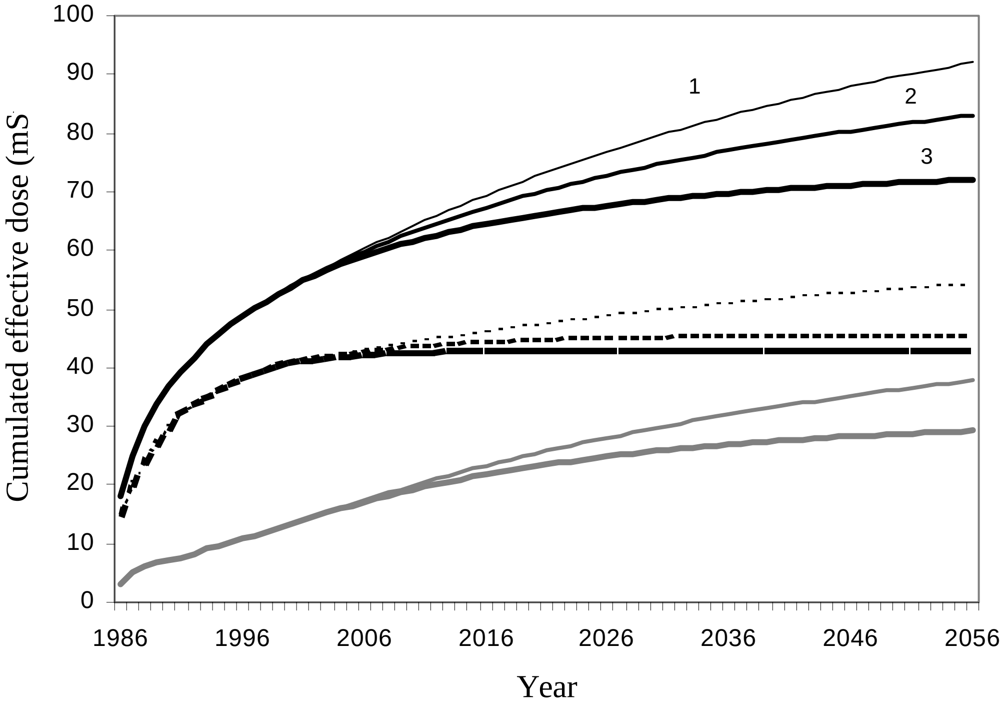

Fig. 4. Cumulated effective dose between 1986 and 2056 assuming various annual rates of decrease for the external and internal effective dose after 2000. The two lower curves represent the internal cumulated dose assuming a decrease rate of 2% and 4% per year, respectively, after 2000. The three middle curves represent the external effective dose assuming decrease rates after 2000 of 2%, 8% and 16% per year. The three higher curves represent the sums of the cumulated internal and external doses for different decrease rates after 2000; curve 1 is the sum of external 2% and internal 2%, curve 2 is the sum of external 8% and internal 2% and curve 3 is the sum of external 15% and internal 4%.

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