On the relationship between ambient dose equivalent and absorbed dose in air in the case of large-scale contamination of the environment by radioactive cesium

V. Ramzaev, A. Barkovsky

Saint-Petersburg Research Institute of Radiation Hygiene after Professor P.V. Ramzaev, Rospotrebnadzor,
Saint-Petersburg, Russia

The author's data:

Ramzaev Valery – Candidate of Medical Sciences, Leading Researcher, Saint-Petersburg Research Institute of Radiation Hygiene after Professor P.V. Ramzaev. Address: Mira Str. 8, 197101, Saint-Petersburg, Russia. Tel./fax: +7 812 232 04 54. E-mail: V.Ramzaev@mail.ru.

Barkovsky Anatoly – the Head of the Laboratory of External Exposure, Saint-Petersburg Research Institute of Radiation Hygiene after Professor P.V. Ramzaev. Address: Mira Str. 8, 197101, Saint-Petersburg, Russia. Tel./fax: +7 812 232 04 54. E-mail: ANBarkovski@yandex.ru.

Abstract

One of the main aims of the study was an experimental determination of the conversion coefficient from ambient dose equivalent rate, $\dot{H}^*(10)$, to absorbed dose rate in air, $\dot{D}$, in the case of radioactive contamination of the environment following the Chernobyl accident. More than 800 measurements of gamma-dose rates in air were performed at the typical locations (one-storey residential house, street, yard, kitchen-garden, ploughed field, undisturbed grassland, forest) of rural settlements and their surroundings in the heavily contaminated areas of the Bryansk region, Russia in the period of 1996–2010. Five commercially available models of portable gamma-ray dosimeters were employed in the investigation. All tested dosimeters were included into the State register of approved measuring instruments of Russia. In all dosimeters, scintillation detectors are used as detection elements. A photon spectrometry technique is applied in the dosimeters to determine gamma dose rate in air. The dosimeters are calibrated in terms of exposure rate, $\dot{X}$, absorbed dose rate in air, $\dot{D}$, and ambient dose equivalent rate, $\dot{H}^*(10)$. A very good agreement was found between different dosimeters calibrated in the same units; the reading ratios were close to 1 and the correlation coefficients (Pearson's or Spearman's) were higher than 0.99. The $\dot{H}^*(10)/\dot{D}$ ratio values were location-specific ranging from 1.23 Sv/Gy for undisturbed grasslands and forests to 1.47 Sv/Gy for wooden houses and asphalted streets. A statistically significant negative correlation (Spearman's coefficient = -0.833; P<0.01; n=9) was found between the $\dot{H}^*(10)/\dot{D}$ ratio and the average energy of gamma-rays determined with a NaI(Tl)-based gamma-ray monitor. For the whole area of a settlement and its surroundings, the average ratio of $\dot{H}^*(10)$ to $\dot{D}$ was calculated as 1.33 Sv/Gy. The overall conversion coefficient from ambient dose equivalent rate, $\dot{H}^*(10)$, to external effective dose rate, $\dot{E}$, for adults was estimated by a value of 0.52 Sv/Sv. This value is valid for the remote period after the severe radiation accident that had resulted in large-scale contamination of the environment by radioactive cesium. The findings of this study are discussed in comparison with results obtained by other researches shortly after the Chernobyl and Fukushima accidents.

Key words: *ambient dose equivalent, absorbed dose in air, external effective dose, conversion, Chernobyl, Fukushima, radiocesium.*

Introduction

The issues of compatibility between the new and existing equipment for radiation measurements may arise in long-term (many-years) monitoring studies of radioactive contamination of the environment. Such issues have recently come to the fore in relation to the assessment of external exposure of the population living in the zone of radioactive contamination due to the Chernobyl accident.

Until recent times, many types of gamma-ray dosimeters were calibrated in terms of exposure, *X* (roentgen, R). It is easy to convert this quantity into the physical quantities air kerma, *K* (gray, Gy), and absorbed dose in air (if electronic equilibrium is maintained), *D* (Gy), using the transfer factor *g*, which value practically does not depend on the energy of gamma quanta [1]. For example, a difference between the *g* values in the energy range 50–1250 keV does not exceed 1%. An exposure of 1 R corresponds to an air kerma or absorbed dose (under electronic equilibrium conditions) of 0.0088 Gy [2]. In turn, the physical quantity *K* or *D* can be converted into the principal radiological protection quantity, effective dose, *E* (sievert, Sv), (for example, [3, 4, 5, 6]). It is experimentally demonstrated that, in the Chernobyl contaminated areas of Russia, the conversion factor from *K* (or *D*) to *E* has a negative relationship with the body mass of a subject, ranging from 0.69 Sv/Gy for adults to 0.95 Sv/Gy for infants (Fig. 2 in [7]). The final step of the accidental dose assessing includes: 1) evaluation of the time fractions that a human spends in typical locations (so called "occupancy factors") and 2) calculation of the total effective dose (usually per annum) using values of *K* (or *D*) in typical locations, age-dependant conversion factor from *K* (or *D*) to *E*, and occupancy factors for typical locations [6, 8]. The described dosimetric system allows performing a realistic assessment of the external effective dose to the population living in areas contaminated by radioactive cesium due to the Chernobyl accident.

Now, most of commercially manufactured gamma-ray dosimeters are calibrated in terms of operational quantities, specifically in the units of ambient dose equivalent, $H^*(10)$ (Sv), and/or its rate, $\dot{H}^*(10)$. Within the system of quantities and units in radiation protection dosimetry, the operational quantity $H^*(10)$ is a conservative estimate of the protection quantity E for photon energy up to 10 MeV (for example, [3, 4, 9]). Unfortunately, for specific conditions of irradiation in the radioactively contaminated environment, a degree of such conservatism (overestimation) cannot be predicted without additional calculations or measurements using gamma-ray spectrometers (for example, [10]). The key issue is that the ratio of $H^*(10)$ to E changes depending on irradiation geometry and energy of gamma-quanta (see, e.g. Table A.21. in publication No. 74 ICRP [3] and Table A.2. in publication No. 116 ICRP [4]). The calculated energy dependence of the ratios $H^*(10)/K$ and E/K for rotational and isotropic irradiation geometries, which are most closely related to conditions of the human exposure in the radioactively contaminated environment, is shown in Fig. 1. The ratio of $H^*(10)$ to K increases from 1.19 Sv/Gy to 1.74 Sv/Gy when the energy of photons decreases from 800 keV to 60 keV [3]. For isotropic irradiation of an adult anthropomorphic computational phantom, the conversion coefficient from air kerma to effective dose decreases from 0.708 Sv/Gy to 0.675 Sv/Gy when the photon energy decreases from 800 keV to 300 keV, and then the coefficient increases to 0.773 Sv/Gy when the energy decreases to 80 keV [4]. A similar pattern can be seen with respect to rotational geometry but the E/K ratio for this geometry is sufficiently higher than the one for isotropic geometry (Fig. 1).

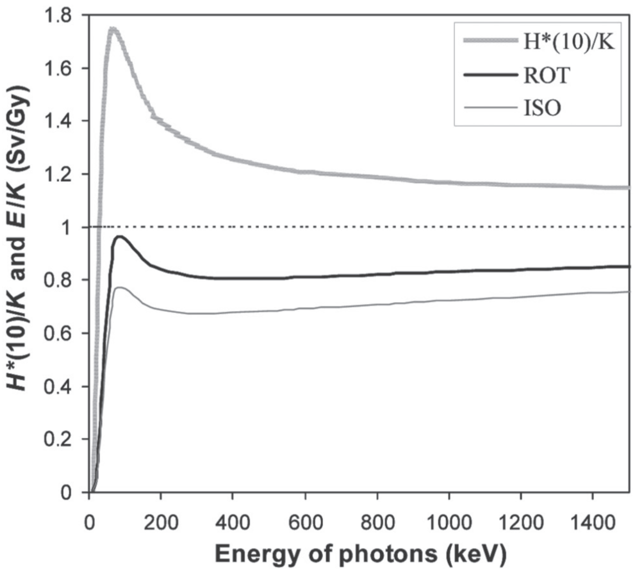

Fig. 1. The ratio of ambient dose equivalent, $H^*(10)$, to air kerma, K, and the ratio of effective dose, E, to K for rotational (ROT) and isotropic (ISO) geometry of irradiation for an adult anthropomorphic computational phantom as a function of photon energy. The figure is based on data in Table A.21. from the document No. 74 ICRP [3] and Table A.2. from the document No. 116 ICRP [4]

The main aim of the study was an experimental determination of conversion coefficient from the operational quantity $H^*(10)$ to the physical quantity D in the case of radioactive contamination of the environment following the Chernobyl accident. There were three objectives of the study: a) to perform intercomparison measurements of gamma dose rate in air using different dosimeters calibrated in the same units; b) to determine the average energy of gamma radiation in air at typical locations inside and outside settlements; c) to compare results of the measurements, which were conducted in the paired mode using dosimeters calibrated in terms of ambient dose equivalent rate, $\dot{H}^*(10)$, and absorbed dose rate in air, $\dot{D}$. The experimental data are included in recommendations for the practical application of the operational quantity $H^*(10)$ in evaluating the protection quantity E in the case of large-scale contamination of the environment by radiocesium.

The study has been conducted since 1996 in the framework of the post-Chernobyl monitoring programs at the territory of the Bryansk region, Russia [8, 11, 12, 13, 14].

Materials and Methods

Instruments

Measurements of gamma dose rates in air were conducted with four types of dosimeters from the firm “ATOMTEX” (Minsk, Belarus) and with the portable spectrometer-dosimeter of gamma and X-ray radiation “SKIF” from the firm “SINKO” (St.-Petersburg, Russia). Scintillation detectors are used in the dosimeters for measurement of gamma radiation energy distribution and gamma radiation dose rate [15, 16, 17]. All dosimeters have been included into the State register of approved measuring instruments of the Russian Federation.

The monitor of gamma-radiation EL 1101 (ATOMTEX) was the principle measuring device. Its external detection unit is based on the standard NaI(Tl) crystal with a diameter of 25 mm and a length of 16 mm. The reading of the dosimeter is calibrated in units of exposure rate, $\dot{X}$, and ambient dose equivalent rate, $\dot{H}^*(10)$. The device also displays the average energy of registered gamma radiation [15]. A method of spectrometric photon dosimetry for determining a gamma dose rate for X-ray and gamma radiation is used in the EL dosimeters. The measured pulse height distribution is converted automatically into the physical quantities of dose rate and average energy of gamma radiation using the response functions that are recorded in the memory unit of the dosimeter. The correction functions (factors) are energy-dependent and related to operation modes.

A part of measurements was conducted with the dosimeter-radiometer MKS-1117 (EL 1117). The device has an external detection unit based on the standard NaI(Tl) crystal which has performance similar to the crystal in the EL 1101. The EL 1117 device is calibrated in units of exposure rate, $\dot{X}$, absorbed dose rate in air, $\dot{D}$, and ambient dose equivalent rate, $\dot{H}^*(10)$ [18].

The tissue-equivalent plastic scintillator with added traces of heavy metals is used as the basis for a detector (30 mm×15 mm) in the modern dosimeters DKS AT-1121 и DKS AT-1123 (ATOMTEX) that have been exploited in our laboratory since 2009 instead of the EL-series dosimeters. Unfortunately the DKS AT dosimeters are calibrated only in terms of ambient dose equivalent, $H^*(10)$, and its rate, $\dot{H}^*(10)$.

For the four above-described dosimeters manufactured by ATOMTEX, the 15% uncertainty (the 95% probability) is assigned to counting efficiency for the 662 keV gamma-rays from ^{137}Cs [16]. Statistical uncertainty of a single measurement was typically in the range 5–7% and it did not exceed 15%. Reference ^{137}Cs sources (activities of 10–12 kBq) were used for periodical calibrations of the EL dosimeters.

The portable spectrometer-dosimeter of gamma and X-ray radiation “SKIF” (SINKO) has a detector based on a NaI(Tl) crystal [63 mm (diam.)×63 mm] and the 480-channel pulse height analyzer [17]. To protect it from physical damage, the detection unit is placed into a cylindrical case which walls are made of 1mm steel.

The energy and efficiency calibrations of the “SKIF” were performed using the reference point sources OSGI-3-2-1p with the activities (on 10 May 1999) of 60 kBq (^{60}Co), 96 kBq (^{137}Cs), 43 kBq (^{152}Eu), 54 kBq (^{228}Th), and 350 kBq (^{241}Am). The sources had been certified in the Russian Federal Center for Measuring, Instrument Testing and Certification (St.-Petersburg). Data and recommendations given in the papers by Grasty et al. [19] and Helfer and Miller [20] were used for the calibration. Gamma-ray spectra were analyzed using the software “SKIF-1.1.” from “SINKO” and EXCEL for Windows. The following components of absorbed dose rate in air are calculated:

– the sum of dose rates due to natural radionuclides (^{40}K, radionuclides from the ^{232}Th and ^{238}U families);

– the dose rate due to primary (unscattered) photons from ^{137}Cs;

– the dose rate due to scattered photons from ^{137}Cs;

– the sum of dose rates due to primary and scattered photons from ^{137}Cs;

– the total dose rate due to the natural radionuclides and ^{137}Cs.

The energy resolution (full width at half-maximum, FWHM) of the “SKIF” detector was measured to be around 8% for the 662 keV photons from ^{137}Cs–^{137m}Ba. The background gamma-ray spectrum, which was used for subtraction from field spectra, had been recorded on the frozen surface of the Finnish gulf in the Leningrad region (Russia). A systematic uncertainty of dose rate measurements with the “SKIF” is estimated as ±20%. Count times of the spectroscopic measurements ranged from 200 s to 600 s (usually 300 s). The statistical uncertainty of evaluation of peak area at 662 keV did not exceed 10% (1 sigma).

In the period of 1996–2009, an aluminum tripod (mass about 4 kg) was used to support the dosimeters. A dosimeter was placed on the tripod at a height of 1 m above the ground with the scintillation detector facing down. In 2010, a person carrying out the survey held the instrument (the devices AT-1121 and AT-1123) in a hand at a distance of about 0.6–0.7 m from the body and at a height of approximately 1 m above the ground (a possible standard geometry according to [21]).

During measurements in the laboratory, the instruments were placed on the tripod at a distance not less than 2 m from the nearest wall. The reference gamma-ray sources were positioned at a distance of 0.3–90 cm from the surface of a detector.

One of our dosimeters, the EL 1101, was tested during the Russian-Danish exercise in the Bryansk region in 1997 [14]. A good agreement was found between results obtained with the EL 1101 and a Reuter-Stokes RSS-112 high-pressure ion chamber (Reuter-Stokes Inc., OH, USA). The registered exposure rates, $\dot{X}$, in both sets of measurements ranged from 20 μR h^{-1} to 140 μR h^{-1}. The combined values of 2.0 μR h^{-1} (EL 1101) and 3.6 μR h^{-1} (RSS 112) for the intrinsic noise and cosmic radiation response were subtracted from the dosimeters reading. After this, the mean ratio between the dose rates determined with the EL 1101 and RSS-112 was 1.01±0.07 (n=20) and the median was 1.01. These estimates are based on Fig. 2 from the report [14] of the RISØ National Laboratory.

Conditions of measurements

Field measurements were carried out at the areas of the 35 settlements located between the latitudes of 52.44–53.10° N and the longitudes of 31.55–32.29° E in the mostly contaminated part of the Bryansk region (oblast) in the Gordeyevskiy, Zlynkovskiy, Klintsovskiy, Krasnogorskiy and Novozybkovskiy districts (raions). Table 1 contains a full list of these settlements, the levels of their contamination by ^{137}Cs (on 1986), and the calendar years when our surveys were conducted. The initial (on 1986) ground deposition of ^{137}Cs in the studied settlements ranged from 110 kBq m^{-2} to 4340 kBq m^{-2} with the mean of 940 kBq m^{-2} and the median of 697 kBq m^{-2}.

The gamma dose rate measurements were conducted in the absence of snow cover, under dry weather during the spring-autumn period. The measurements were performed at the typical locations both outdoor (yard, kitchengarden, street, arable field, virgin grassland, forest) and indoor (one-storey wooden and brick private houses). The houses had been built before the Chernobyl accident. Note that large-scale decontamination was performed in some of the studied settlements after the Chernobyl accident [12, 13, 22]. The ground plots (so called “yards” located near private and public buildings) and streets were the main targets for decontamination measures.

The absorbed gamma dose rates in air due to natural radionuclides at the study area range from 18±5 nGy h^{-1} in forest to 54±11 nGy h^{-1} inside brick and panel houses [8]. Let us evaluate expected ambient dose equivalent rates, $\dot{H}^*(10)$, for these absorbed gamma dose rates from natural radionuclides. It is known that the average energy of gamma quanta at a height of 1 m above the ground for the ^{238}U family, ^{232}Th family, and ^{40}K (assuming a vertically homogeneous distribution) is equal to 0.37 MeV, 0.41 MeV, and 0.55 MeV, respectively [23]**.** For the “standard” soil-type (the ratio of activities ^{238}U:^{232}Th:^{40}K = 1:1:10 [23]), the mean energy of gamma radiation is 0.44 MeV. A value of conversion coefficient from K to $H^*(10)$ is approximately equal to 1.25 Sv/Gy for this energy of photons [3]. The ratio of activities ^{238}U:^{232}Th:^{40}K in soils from the south-western districts of Bryansk Region is near 1:1:20 [8], and the mean energy of gamma radiation in air can be estimated here by a value of 0.46 MeV. The corresponding conversion coefficient from K to $H^*(10)$ can be computed as 1.25 Sv/Gy. By using this coefficient and experimental data from the study by Ramzaev et al. [8], the ambient dose equivalent rates, $\dot{H}^*(10)$, from the natural radionuclides can be estimated for the typical locations in the Bryansk region as following: 22 nSv h^{-1} (forest), 25 nSv h^{-1} (grassland), 31 nSv h^{-1} (arable field), 30 nSv h^{-1} (yards with ground cover), 31 nSv h^{-1} (kitchengarden), 52 nSv h^{-1} (asphalted streets and yards), 40 nSv h^{-1} (one-storey house, wood), 62 nSv h^{-1} (one-storey house, brick or panel).

Table 1

Levels of the ^{137}Cs ground deposition (on 1986) [34] in 35 settlements surveyed in the Bryansk region

District	Settlement	^{137}Cs ground deposition (kBq m^{-2})	The year of the survey
Klintsovskiy	Smolevichi	110	1996
Klintsovskiy	Blizna	155	1996
Klintsovskiy	Berezovka	240	1996
Klintsovskiy	Lopatny	249	1996
Klintsovskiy	Klincy	317	1996
Klintsovskiy	Cherny Ruchey	356	1996
Klintsovskiy	Rogny	361	1996
Klintsovskiy	Tulukovshina	419	1996
Klintsovskiy	Olhovka	449	1996
Klintsovskiy	Guta-Koreckaja	470	1996
Novozybkovskiy	Snovskoe	477	2009, 2010
Novozybkovskiy	Manuki	566	2010
Klintsovskiy	Unecha	601	1996
Gordeyevskiy	Smjalch	635	1996
Klintsovskiy	Uscherpie	656	1996, 2000, 2009,2010
Novozybkovskiy	Mamay	684	2000, 2009,2010
Novozybkovskiy	Sinavka	696	2000, 2009,2010
Novozybkovskiy	Novozybkov	697	1996, 1998, 2000, 2009,2010
Novozybkovskiy	Vereschaki	701	2010
Novozybkovskiy	Dubrovka	784	2009, 2010
Klintsovskiy	Veprin	853	1996, 2000, 2009,2010
Novozybkovskiy	Starie Bobovichi	1037	2010
Zlynkovskiy	Dobrodeevka	1088	2010
Novozybkovskiy	Novie Bobovichi	1094	1997, 2000, 2009,2010
Novozybkovskiy	Yasnaya Polyana	1101	2000, 2009,2010
Zlynkovskiy	Muravinka	1133	2000, 2009,2010
Zlynkovskiy	Vishkov	1157	2010
Novozybkovskiy	Demenka	1167	2000, 2009,2010
Zlynkovskiy	Barki	1198	2000, 2009,2010
Novozybkovskiy	Griva	1205	2000, 2009,2010
Novozybkovskiy	Stariy Vishkov	1471	1996, 2000, 2009,2010
Novozybkovskiy	Svjatsk	1493	2000, 2009,2010
Novozybkovskiy	Babaki	2186	1998, 2000, 2009,2010
Krasnogorskiy	Yalovka	2766	2010
Krasnogorskiy	Zaborie	4340	1996, 2010

Statistical treatment of results

Statistical analysis of the measurements results included calculation of the median, mean, standard deviation (SD) and coefficient of variation (CV). Difference between groups was tested using the non-parametric Mann-Whitney test for independent samples. Pearson's correlation coefficient (a large data sample; n>60) or Spearman's rank correlation coefficient (a small data sample) was calculated to determine a degree of correlation between variables. A linear regression analysis was also applied with calculation of coefficients in the regression equation and presentation of the obtained results in figures. Statistically significant difference was defined if the P-value was less than 0.05. The statistical analysis was performed using Microsoft Excel for Windows and Codes for the Automatic Calculations [24].

Results and Discussion

Intercomparison measurements of dose rates

Table 2 provides summary statistics of measured dose rates for each instrument in four series of paired measurements. The values of dose rates in Table 2 are presented after subtracting the devices intrinsic noise and cosmic radiation response. A scatter of dose rate values in each data sample was rather large, about an order of magnitude. Note that the mean and median values of the total dose rates were much higher than the corresponding parameters of the air dose rates due to natural radionuclides. Because of this, a possible difference between the devices responses for the anthropogenic radiation and the natural radiation has been neglected.

Summary statistics of the calculated ratios of dose rates for the four pairs of tested instruments are given in Table 3.

A very good agreement was found between results of exposure rate measurements conducted with the EL 1101 and EL 1117 dosimeters in the Novozybkov district in 1998 (Fig. 2). Spearman's coefficient of correlation, R_{Sp}, was calculated as 1.0 ($P<0.01$; $n=11$). The mean and median ratios of the $\dot{X}$ values obtained with the EL 1101 and EL 1117 are nearly identical: 1.01 and 1.00, respectively; the CV of the ratio is equal to 4% (Table 3).

The monitoring studies, which were conducted in the areas of 15 settlements from the Zlynkovskiy, Klinzovskiy and Novozybkovskiy districts in 2000, demonstrate an excellent coincidence between the dosimeter EL 1101 and dosimeter-radiometer "SKIF" with respect to absorbed dose rate in air, $\dot{D}$ (Fig. 3). Pearson's coefficient of correlation, R_P, was calculated as 0.998 ($P<0.001$; $n=114$). The mean and median ratios of the $\dot{D}$ values determined with the EL 1101 vs. SKIF are calculated as 1.00. The CV of the ratio is equal to 5%.

A strong positive correlation has been found between results obtained in 2010 with the DKS-AT1121 and DKS-AT1123, the devices that are calibrated in terms of ambient dose equivalent rate (Fig. 4). Pearson's coefficient of correlation, R_P, is 0.993 ($P<0.001$; $n=138$). The mean and median ratios of the $\dot{H}^*(10)$ values obtained in the paired measurements with the DKS-AT1121 vs. DKS-AT1123 are calculated as 1.00. The CV value of the ratio is 7%.

The perfect positive correlations between results obtained with the tested devices (the EL family, DKS-AT family and "SKIF") in the series of paired measurements are not random. Calibrations of the dosimeters were conducted using reference point sources from the same metrological institute, the Russian Federal Center for Measuring, Instrument Testing and Certification (St.-Petersburg). Besides this, the photon spectrometry technique was used in all tested dosimeters. Therefore, any of the dosimeters in principle could serve adequately as a basic device for evaluating the coefficient of conversion from $\dot{D}$ to $\dot{H}^*(10)$ and visa versa.

Table 2

Gamma dose rates determined in the four series of paired measurements in the Bryansk region in 1998–2010

Year	Device	Parameter							
		Quantity	Unit	n	Range	Median	Mean	SD	CV (%)
1998	EL 1101	$\dot{X}$	μR h⁻¹	11	7–208	63	63	59	94
1998	EL 1117	$\dot{X}$	μR h⁻¹	11	7–203	66	63	57	90
2000	SKIF	$\dot{D}$	nGy h⁻¹	114	92–1960	549	569	372	65
2000	EL 1101	$\dot{D}$	nGy h⁻¹	114	91–1890	537	569	373	66
2010	AT 1121	$\dot{H}^*(10)$	nSv h⁻¹	138	130–1850	423	482	277	57
2010	AT 1123	$\dot{H}^*(10)$	nSv h⁻¹	138	126–1740	410	482	270	56
2009	AT 1121	$\dot{H}^*(10)$	nSv h⁻¹	99	92–1690	453	480	279	58
2009	SKIF	$\dot{D}$	nGy h⁻¹	99	53–1420	371	381	237	62

n – number of measurements; SD – standard deviation; CV – coefficient of variation.
The dose rate values are shown after correction for the intrinsic noise of the dosimeters and their response to cosmic radiation.

Table 3

Gamma dose rates ratios estimated from the four series of paired measurements in the Bryansk region in 1998–2010 (see Table 2)

Year	Devices	Parameter							
		Quantities	Units	n	Range	Median	Mean	SD	CV (%)
1998	(EL 1101)/(EL 1117)	$\dot{X}/\dot{X}$	R/R	11	0.95–1.06	1.00	1.01	0.04	4
2000	(SKIF)/(EL 1101)	$\dot{D}/\dot{D}$	Gy/Gy	114	0.85–1.21	1.00	1.00	0.05	5
2010	(AT 1121) /(AT 1123)	$\dot{H}^*(10)/ \dot{H}^*(10)$	Sv/Sv	138	0.83–1.22	1.00	1.00	0.07	7
2009	(AT 1121) /(SKIF)	$\dot{H}^*(10)/\dot{D}$	Sv/Gy	99	1.10–1.75	1.28	1.31	0.13	10

n – number of measurements; SD – standard deviation; CV – coefficient of variation.

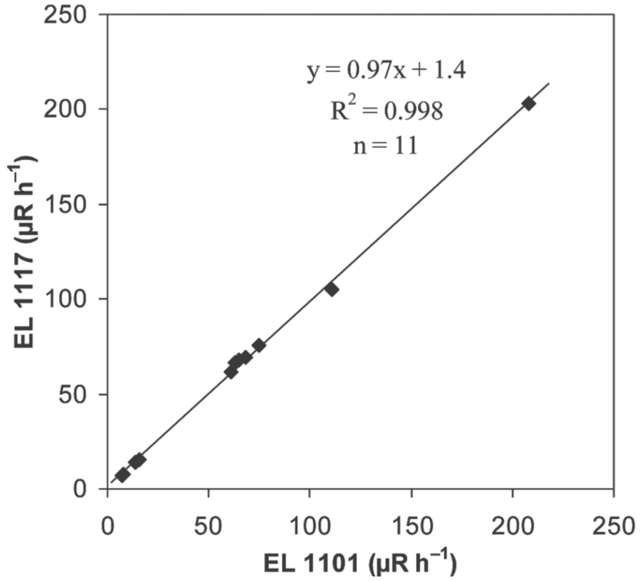

Fig. 2. Relationship between the exposure rates ($\dot{X}$) measured with the dosimeters EL 1101 and EL 1117 at 11 sites in the Novozybkovskiy district of the Bryansk region in 1998. The data are shown after correction for the intrinsic noise of the devices and their response to cosmic radiation

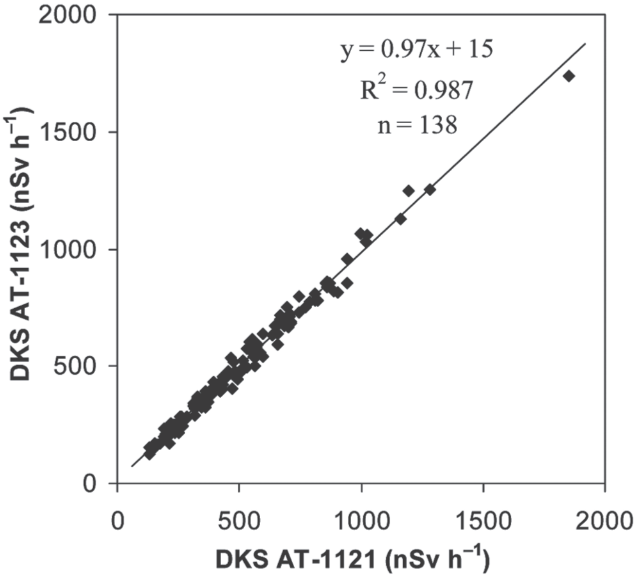

Fig. 4. Relationship between the ambient dose equivalent rates ($\dot{H}$*(10)) determined with the dosimeters DKS AT-1121 and DKS AT-1123 at 138 sites in the south-western districts of the Bryansk region in 2010. The data are shown after correction for the intrinsic noise of the devices and their response to cosmic radiation

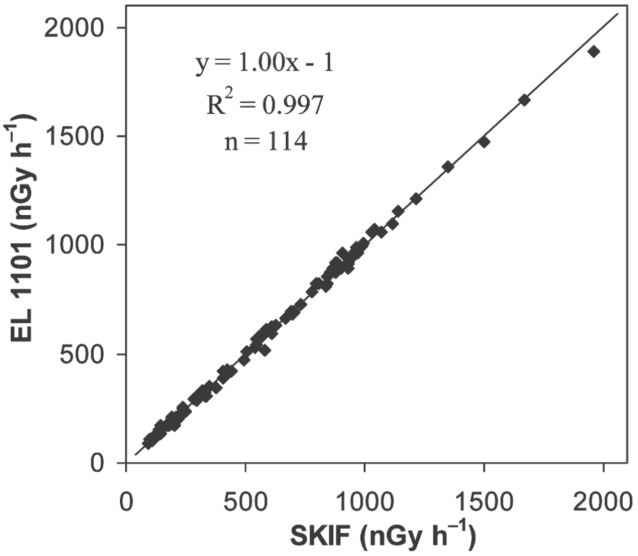

Fig. 3. Relationship between the absorbed dose rates in air ($\dot{D}$) determined with the devices EL 1101 and "SKIF" at 114 sites in the south-western districts of the Bryansk region in 2000. The data are shown after correction for the intrinsic noise of the devices and their response to cosmic radiation

The average energy of gamma radiation in air at typical locations

Taking into account the fact that the conversion coefficients *H**(10)/*D* and *H**(10)/*K* depend on the energy of gamma quanta (Fig. 1), it was interesting to determine a range of the average energy of gamma radiation in air at typical locations. The measurements of dose rates and the average energy were conducted with the device EL 1101 in 17 settlements from the Gordeevskiy, Klinzovskiy, Krasnogorskiy and Novozybkovskiy districts in 1996.

Data for 132 surveyed sites are summarized in Table 4. The average energy of gamma radiation varied from 190 keV to 330 keV. The maximum values (around 300 keV) were registered at forests and virgin grasslands, i.e. at those locations where a relatively shallow penetration depth of ^{137}Cs in soil was observed [8]. The 662 keV primary (unscattered) photons from ^{137}Cs dominated total anthropogenic gamma-ray dose at these locations [25]. The lowest values of the average energy (around 200 keV) were registered inside wooden houses and in the center of the streets covered with asphalt. At other locations (yard, kitchengarden, arable field), the average energy was close to 240 keV. The non-parametric Mann-Whitney test was applied in order to test if the observed differences between the average energies at different locations are statistically significant. Results of the test are presented in Table 5, from which one can see that the differences between locations belonging to the group "house and street" from one hand, and all other locations from the other hand, are statistically significant ($P<0.01$). An analogous conclusion can be drawn with respect to locations belonging to the group "grassland and forest". The similar quantitative differences in the average energy between different locations were found at the radioactively contaminated territories of the Soviet Union in summer 1987, i.e. approximately 1.1–1.3 years after the Chernobyl accident [26]. In this time period, the average energy of gamma-radiation in air for the locations: forest, grassland, arable field, yard, and wooden house was calculated as: 360 keV, 370 keV, 270 keV, 300 keV, and 240 keV, respectively. One can see that these values of the average energy are higher than those registered in 1996 in our study (Table 4). The inter-yearly differences are associated, first of all, with a much shallower activity depth profile of fallout radionuclides in soil in 1987, and second, with the presence of a large proportion of ^{134}Cs (half-life = 2.06 y) in the radioactive contamination in 1987. The radionuclide has a higher average energy of primary gamma-radiation (698 keV) than the one from ^{137}Cs–^{137m}Ba (662 keV) [27]. Note that the initial ^{134}Cs/^{137}Cs activities ratio in Chernobyl fallout was near 0.55 [28], while the gamma rays yield per disintegration is 0.85 for ^{137}Cs and 2.23 for ^{134}Cs [27].

In 1996, the calculated average energy (near 250 keV) of gamma-radiation at all locations in the Bryansk region appeared to be much lower than the primary energy (662 keV) of gamma quanta from ^{137}Cs–^{137m}Ba. Therefore the $H^*(10)/D$ values, expected for the contaminated environment in 1996, will be sufficiently larger than a value of 1.20 Sv/Gy calculated for the primary energy (662 keV) of gamma rays from ^{137}Cs. Specifically, a scatter between 1.42 Sv/Gy and 1.29 Sv/Gy could be assessed for the energy range 190–330 keV.

Relationship between operational and physical quantities

Our first field verification of relationship between physical and operational quantities was conducted at four typical outdoor locations in the Novozybkovskiy district in July 1998 (Table 6). The mean ratios $\dot{H}^*(10)/\dot{X}$ and $\dot{H}^*(10)/\dot{D}$ were determined as 0.0113 Sv/R and 1.28 Sv/Gy, respectively, and the CV values were near 2%. A regression analysis shows that the small fluctuations of the ratios $\dot{H}^*(10)/\dot{X}$ and $\dot{H}^*(10)/\dot{D}$ are associated with variations in the average energy of gamma radiation. The ratio of $H^*(10)$ to D (Fig. 5) has appeared to be negatively correlated with the average energy registered using the device EL 1101 (columns 4 and 10 in Table 6). This relationship is statistically significant and strong; Spearman's coefficient of correlation, R_{Sp}, was -0.833 ($P<0.01$; n=9). The relationship for the pair [$\dot{H}^*(10)/\dot{X}$]/[average energy] (data are not shown in a scatter-plot) display features similar to those obtained for the pair [$\dot{H}^*(10)/\dot{D}$]/[average energy]. Spearman's coefficient of correlation, R_{Sp}, was -0.858 ($P<0.01$; n=9).

A negative relationship between the $\dot{H}^*(10)/\dot{D}$ ratio and the average energy of gamma-radiation was found in laboratory experiments with the dosimeter EL 1117 and the reference point sources OSGI-1-2-3p. A distance between the detector and the source was 5 cm. For the ^{60}Co source (the average energy of primary photons=1250 keV), the $\dot{H}^*(10)/\dot{D}$ conversion coefficient was calculated as 1.11±0.01 Sv/Gy (n=5). For the ^{137}Cs source (energy of primary photons=662 keV), the $\dot{H}^*(10)/\dot{D}$ conversion coefficient appeared to be higher, 1.19±0.01 Sv/Gy (n=5). The difference between the two series of measurements is statistically significant ($P<0.05$, the Mann-Whitney test).

Table 4

Exposure rate, $\dot{X}$, and the average energy of gamma radiation determined with the dosimeter EL 1101 at typical locations in the Bryansk region in 1996

Location	n	$\dot{X}$ (μR h^{-1})					Average energy (keV)				
		Range	Median	Mean	SD	CV (%)	Range	Median	Mean	SD	CV (%)
house	24	10–35	22	23	7	30	197–240	214	215	12	6
street	23	23–94	51	50	23	46	191–249	212	216	17	8
yard	23	25–151	55	63	36	57	202–275	238	235	19	8
kitchengarden	24	55–209	74	96	49	51	230–255	243	243	8	3
arable field	8	18–79	47	44	21	48	222–263	247	247	13	5
grassland	13	11–131	36	51	37	73	274–331	296	299	16	5
forest	17	19–184	54	67	44	66	287–331	308	309	13	4

n – number of measurements; SD – standard deviation; CV – coefficient of variation.
The dose rate values are shown without correction for the intrinsic noise of the dosimeter and its response to cosmic radiation.

Table 5

Levels of statistical significance (P-value, the Mann-Whitney test) in differences between different locations with respect to the average energy of gamma-radiation in air determined with the dosimeter EL 1101 at typical locations in the Bryansk region in 1996 (see Table 4)

Location	house	street	yard	kitchengarden	arable field	grassland	forest
house	0	-	-	-	-	-	-
street	**>0.05**	0	-	-	-	-	-
yard	<0.01	<0.01	0	-	-	-	-
kitchengarden	<0.01	<0.01	<0.05	0	-	-	-
arable field	<0.01	<0.01	<0.05	**>0.05**	0	-	-
grassland	<0.01	<0.01	<0.01	<0.01	<0.01	0	-
forest	<0.01	<0.01	<0.01	<0.01	<0.01	**>0.05**	0

Table 6

Gamma dose rate in air, the average energy of gamma radiation, and relationship between physical and operational quantities for the nine reference sites in the Novozybkov district of the Bryansk region in 1998

Plot code	Location	Dosimeter EL 1101		Dosimeter EL 1117					
		$\dot{X}$ (μR h^{-1})	Average energy (keV)	$\dot{X}$ (μR h^{-1})	$\dot{D}$ (μGy h^{-1})	$\dot{H}^*(10)$ (μSv h^{-1})	D/X (Gy/R)	$H^*(10)/X$ (Sv/R)	$H^*(10)/D$ (Sv/Gy)
F-1	yard	16	208	15.7	0.139	0.181	0.00885	0.0115	1.30
F-2	yard	18	224	17.1	0.152	0.198	0.00889	0.0116	1.30
Ba-1	arable field	63	257	63.8	0.560	0.717	0.00878	0.0112	1.28
Ba-2	arable field	65	211	68.4	0.603	0.785	0.00882	0.0115	1.30
Ba-3	arable field	67	211	69.7	0.612	0.791	0.00878	0.0113	1.29
Ba-4	arable field	70	231	71.4	0.627	0.808	0.00878	0.0113	1.29
F-3	forest	77	310	77.3	0.678	0.845	0.00877	0.0109	1.25
NB-1	grassland	113	300	107.2	0.940	1.184	0.00877	0.0110	1.26
Ba-5	grassland	210	305	205	1.796	2.247	0.00876	0.0110	1.25
Median		67	231	69.7	0.612	0.791	0.00878	0.0113	1.29
Mean		78	251	77.3	0.679	0.862	0.00880	0.0113	1.28
SD		58	43	55.9	0.489	0.608	0.00004	0.0002	0.02
CV (%)		74	17	72	72	71	0.5	2.2	1.7

SD – standard deviation; CV – coefficient of variation.
Statistical uncertainty of each measurement was in the range 3–5%.
The dose rates values are shown without correction for the intrinsic noise of the dosimeters and their response to cosmic radiation.

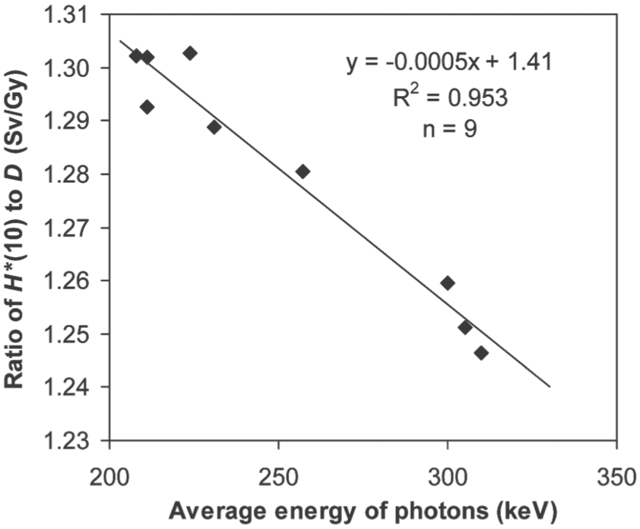

Fig. 5. The ratio of ambient dose equivalent, $\dot{H}^*(10)$, to absorbed dose in air, $\dot{D}$, as a function of photon energy. The measurements were performed with the dosimeters EL 1117 and EL 1101 at nine reference sites in the Novozybkovskiy district of the Bryansk region in 1998. The dose rates ratio has been calculated without correction for the intrinsic noise of the dosimeters and their response to cosmic radiation

In order to determine the $\dot{H}^*(10)/\dot{D}$ ratio for the new family of DKS-AT dosimeters, field measurements of dose rates were conducted in 2009 at 15 heavily contaminated settlements using the device "SKIF" as the basic dosimeter. Summary statistics of the results obtained are shown in Tables 2 and 3, while a distribution between individual locations is given in Table 7. Geographical positions of the measurement sites in 2009 mainly repeated the positions of those sites that had been surveyed in 2000 when a very good agreement between the SKIF and EL 1101 had been found (Table 3, Fig. 3). In 2009, a strong positive correlation (R_p = 0.996; P<0.001; n=99) was found between the absorbed dose rates determined with the spectrometer-dosimeter "SKIF" and the ambient dose equivalent rates measured using the dosimeter DKS AT-1121 (Fig. 6). Calculated values of the $\dot{H}^*(10)/\dot{D}$ ratio were within the range 1.10–1.74 Sv/Gy. The wide range of the $\dot{H}^*(10)/\dot{D}$ ratio values can be attributed to: a) statistical uncertainty of the dose rate measurements (up to 15%) and b) variations in the scattered to primary radiation relationship between tested locations. It is known [25, 26, 29] that in remote period after the Chernobyl accident, primary (unscattered) quanta from radiocesium dominates the air gamma dose at forests and virgin grasslands. At the same time, the scattered radiation dominates the air dose at wooden and brick houses, as well as at decontaminated plots [25, 29].

As it had been expected, the lowest median and mean values of the $\dot{H}^*(10)/\dot{D}$ ratio (1.23 Sv/Gy) were deduced for virgin grasslands and forests, while the maximum those (near 1.45 Sv/Gy) were calculated for wooden houses and the streets covered by asphalt (Table 8). The Mann-Whitney test shows that the differences between these two opposite groups are statistically significant at P<0.01 (Table 9). Other locations (yard, kitchengarden, arable field) occupied an intermediate position. The mean and median values of the $\dot{H}^*(10)/\dot{D}$ ratios were nearly identical: 1.34 Sv/Gy and 1.33 Sv/Gy, respectively (Table 8). Such values of the $H^*(10)/K$ ratio correspond to the photon energy of 250 keV (see Table A.21 in the publication № 74 ICRP [3]). A value of 250 keV correlates well with the mean energy of gamma radiation measured at typical location in 1996 (Table 4); it is also in a good agreement with field results obtained in 1998 (Table 6).

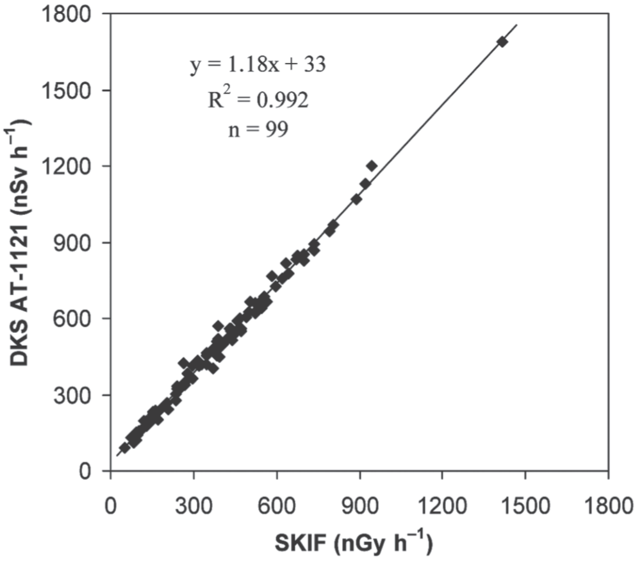

Fig. 6. Relationship between the absorbed dose rates in air, $\dot{D}$, determined with the spectrometer-dosimeter “SKIF”, and the ambient dose equivalent rates, $\dot{H}^*(10)$, determined with the dosimeter DKS AT-1121 at 99 sites in the south-western districts of the Bryansk region in 2009. The data are presented after correction for the intrinsic noise of the devices and their response to cosmic radiation

Table 7

Ambient dose equivalent rate, $\dot{H}^*(10)$, and absorbed dose rate in air, $\dot{D}$, at typical locations in the Bryansk region in 2009

Location	n	Dose rate							
		$\dot{H}^*(10)$ (nSv h^{-1})				$\dot{D}$ (nGy h^{-1})			
		Range	Median	Mean	SD	Range	Median	Mean	SD
house	4	92–140	117	116	20	53–95	88	81	20
street	7	133–348	233	213	74	76–269	160	151	66
yard	13	178–572	227	288	124	130–391	173	208	81
kitchengarden	6	228–597	449	432	119	154–469	346	338	103
arable field	26	151–664	318	351	160	100–503	240	272	136
grassland	19	488–1690	664	780	299	395–1420	545	637	250
forest	24	332–1120	556	628	195	269–922	452	516	164

n – number of measurements; SD – standard deviation; CV – coefficient of variation.
The paired measurements were conducted with the dosimeter DKS AT 1121 ($\dot{H}^*(10)$) and the spectrometer-dosimeter “SKIF” ($\dot{D}$).
The dose rates values are shown after correction for the intrinsic noise of the dosimeters and their response to cosmic radiation.

Table 8

The $\dot{H}^*(10)/\dot{D}$ ratios (Sv/Gy) determined for typical locations in the Bryansk region in 2009

Location	n	$\dot{H}^*(10)/\dot{D}$ (Sv/Gy)				
		Range	Median	Mean	SD	CV (%)
house	4	1.28–1.74	1.42	1.47	0.20	14
street	7	1.29–1.75	1.43	1.47	0.18	12
yard	13	1.17–1.61	1.37	1.37	0.12	8.8
kitchengarden	6	1.18–1.50	1.30	1.31	0.10	7.6
arable field	26	1.14–1.63	1.34	1.33	0.12	9.0
grassland	19	1.17–1.32	1.23	1.23	0.04	3.3
forest	24	1.10–1.33	1.23	1.23	0.05	4.1
Median			1.34	1.33	0.12	8.8
Mean			1.33	1.34	0.12	8.4
SD			0.08	0.10	0.06	3.8
CV (%)			6.2	7.4	52	46

n – number of measurements; SD – standard deviation; CV – coefficient of variation.
The paired measurements were conducted with the dosimeter DKS AT 1121 ($\dot{H}^*(10)$) and the spectrometer-dosimeter SKIF ($\dot{D}$) (see Table 7).

Table 9

Levels of statistical significance (P-value, the Mann-Whitney test) in differences between different locations with respect to the $\dot{H}^*(10)/\dot{D}$ ratio in 2009 (see Table 8)

Location	house	street	yard	kitchengarden	arable field	grassland	forest
house	0	-	-	-	-	-	-
street	**>0.05**	0	-	-	-	-	-
yard	**>0.05**	**>0.05**	0	-	-	-	-
kitchengarden	**>0.05**	<0.05	**>0.05**	0	-	-	-
arable field	**>0.05**	<0.05	**>0.05**	**>0.05**	0	-	-
grassland	<0.01	<0.01	<0.01	<0.05	<0.01	0	-
forest	<0.01	<0.01	<0.01	<0.05	<0.01	**>0.05**	0

Calculation of effective dose

Conversion factor from ambient dose equivalent rate, $\dot{H}^*(10)$, to effective dose rate, $\dot{E}$, can be calculated using the conversion factor, A_t (Gy/Sv), from $H^*(10)$ to absorbed dose in air, D (or air kerma, K), and the conversion factor, B_w (Sv/Gy), from D to E. Therefore in the case of large-scale contamination of the environment by radiocesium, the following formula for calculation of external effective dose rate, $\dot{E}_{Cs}$, is applicable:

$$\dot{E}_{Cs} = [\dot{H}^*(10)_{\text{reading}} - \dot{H}^*(10)_{\text{cos+int}} - \dot{H}^*(10)_{\text{NRN}}] \times A_t \times B_W, \qquad (1)$$

where, $\dot{E}_{Cs}$ is external effective dose rate due to the radioactive contamination at the site (location) of measurement, nSv h^{-1}; $\dot{H}^*(10)_{\text{reading}}$ is the dosimeter reading at the site (location) of measurement, nSv h^{-1}; $\dot{H}^*(10)_{\text{cos+int}}$ is the dosimeter reading registered on the surface of a large water body (it reflects a sum of intrinsic noise of the dosimeter and its response to cosmic radiation), nSv h^{-1}; $\dot{H}^*(10)_{\text{NRN}}$ is the gamma dose rate due to natural radionuclides at the site (location) of measurement, nSv h^{-1}; A_t is conversion factor from ambient dose equivalent, $H^*(10)$, to absorbed dose in air, D, for the time period (after accident), t, Gy/Sv; B_w is conversion factor from absorbed dose in air, D, or kerma, K, to effective dose, E, for a human with body mass W, Sv/Gy.

The values of $\dot{H}^*(10)_{\text{NRN}}$ for different locations at the south-western districts of the Bryansk region are given above in subsection "Conditions of measurements". We should note that values of $\dot{H}^*(10)_{\text{NRN}}$ may vary significantly in Russia as well as at other regions of the world (see, for example, [30]). Therefore an experimental determination of the region-specific radiation doses due to natural sources is needed.

Results of the field measurements conducted in the framework of this study in 2009 show that the location specific mean values of A_t lie in a relatively narrow range of 0.68–0.81 Gy/Sv (1.23–1.47 Sv/Gy). By taking into account the data from the 1996, 1998 and 2009 surveys (Tables 4, 6 and 8), an unified coefficient of conversion, A_t, of 0.75 Gy/Sv (1.33 Sv/Gy) can be calculated for all surveyed locations in the period 1996–2009 (10–20 years after the accidental contamination). The derived value of the conversion coefficient A_t can be used for external dose assessment in the late period after the nuclear accident that had resulted in massive fallout of radioactive cesium.

In the early period (1–2 years) after the radioactive fallout, the $H^*(10)/D$ ratio should be lower than 1.33 Sv/Gy, mostly because of a very limited vertical migration of radiocesium in soil. Specifically, the $H^*(10)/D$ ratio was estimated as 1.23 Sv/Gy in the settlements of MinamiSoma-shi and Iitate-mura (Fukushima Prefecture, Japan) after the Fukushima accident [10]. This estimation was done based on the gamma-ray spectra that had been recorded indoor and outdoor one year after the accident. Note that the initial activity ratio of ^{134}Cs/^{137}Cs in Fukushima fallout (on March 2011) was near 1:1 [31, 32]. In this case, the average energy of gamma radiation in air will be slightly higher than the one that may be expected for the ^{137}Cs deposition alone.

The B_W values experimentally derived by Golikov et al. [7] in the Chernobyl contaminated areas are equal to: 0.69 Sv/Gy for an adult (W = 70 kg), 0.82 Sv/Gy for a child of five years old (W = 20 kg), and 0.87 Sv/Gy for a child of one year old (W = 10 kg). These values of B_W have been calculated using equation:

$$B_W = 1.13 \times e^{(-0.12 \times W^{0.33})}, \qquad (2)$$

where B_W is the ratio E/D (Sv/Gy) for a human with body mass W; 1.13 is an empirical coefficient with dimension Sv/Gy; -0.12 is an empirical coefficient with dimension kg^{-1}; W is the mass of a human body, kg [7].

Therefore, for the Chernobyl contaminated areas in the late post-accidental time period, the unified conversion coefficients (Sv/Sv) from ambient dose equivalent rate, $\dot{H}^*(10)$, to effective dose rate, $\dot{E}_{Cs}$, can be calculated as 0.52 (adults), 0.62 (children of 5 years old) and 0.65 (children of 1 year old). The $E/H^*(10)$ ratio of 0.6 Sv/Sv (rounded from 0.59 Sv/Sv) was used in the dosimetric system applied by Akahane et al. [33] for the external dose estimations in adults in the early phase (March 12 – July 11 2011) of the Fukushima accident. The value of 0.6 Sv/Sv, which was adopted by the Japanese researchers [33] in the acute phase of the Fukushima accident, reasonably exceeds the value of 0.52 Sv/Sv deduced in our study in the remote period after the Chernobyl accident. After correction for the age factor (see Fig. 4 in [33]), the $E/H^*(10)$ ratio in the early phase of the Fukushima accident could be estimated as 0.71 Sv/Sv for children of 5 years old and 0.76 Sv/Sv for children of 1 year old.

Conclusions

Air gamma dose rates measurements, which were conducted with five types of portable dosimeters at the radioactively contaminated districts of the Bryansk region in 1996–2010, demonstrated a very good agreement between the devices tested. Coefficients of correlation between the dose rates determined in the paired measurements using two different types of dosimeters exceed a value of 0.99, while the average ratios between the dose rates measured in such mode deviate from 1 not more than by 2%.

The average ratio of ambient dose equivalent to absorbed dose in air ($H^*(10)/D$) was estimated for the study area by a value of 1.33 Sv/Gy that is higher than the value of 1.20 Sv/Gy expected for primary gamma radiation from a ^{137}Cs source. A value of the $H^*(10)/D$ ratio depended on location; the minimum value of 1.23 Sv/Gy were derived for virgin grasslands and forests, while the maximum value of 1.47 Sv/Gy was calculated for the asphalted streets and private wooden houses. The $H^*(10)/D$ ratio values, which were determined for the nine individual sites of measurements, are negatively correlated with the values of the average energy of gamma radiation registered at the same points. This relationship is statistically significant; Spearman's coefficient of correlation was -0.833 ($P<0.01$; n=9).

In the remote time period after the Chernobyl accident, the generalized conversion coefficient from ambient dose equivalent rate, $\dot{H}^*(10)$, to external effective dose rate, $\dot{E}_{Cs}$, for adult population was estimated as 0.52 Sv/Sv. The Japanese investigators [33] used a slightly higher value of 0.6 Sv/Sv for this coefficient in estimating the external doses to adults in the early phase of the Fukushima accident.

The data obtained in this study should be taken into consideration to avoid possible “jumps” between estimations of external doses for population in long-term monitoring studies, especially when different types of dosimeters are used in different years.

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