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Current Concentration of Artificial Radionuclides and Estimated Radiation Doses from ^{137}Cs around the Chernobyl Nuclear Power Plant, the Semipalatinsk Nuclear Testing Site, and in Nagasaki

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Chernobyl Nuclear Power Plant/Effective dose/Gamma spectrometry/Radiation exposure potency/ Semipalatinsk Nuclear Testing Site.

To evaluate current environmental contamination and contributions from internal and external exposure due to the accident at the Chernobyl Nuclear Power Plant (CNPP) and nuclear tests at the Semipalatinsk Nuclear Testing Site (SNTS), concentrations of artificial radionuclides in edible mushrooms, soils and stones from each area were analyzed by gamma spectrometry. Annual effective doses were calculated for each area from the cesium contamination. Calculated internal effective doses of ^{137}Cs due to ingestion of mushrooms were 1.8×10^{-1} mSv/year (y) in Gomel city (around CNPP), 1.7×10^{-1} mSv/y in Korosten city (around CNPP), 2.8×10^{-4} mSv/y in Semipalatinsk city, and 1.3×10^{-4} mSv/y in Nagasaki. Calculated external effective doses of ^{137}Cs were 3.4×10^{-2} mSv/y in Gomel city, 6.2×10^{-2} mSv/y in Korosten city, 2.0×10^{-4} mSv/y in Semipalatinsk city, and 1.3×10^{-4} mSv/y in Nagasaki. Distribution of radionuclides in stones collected beside Lake Balapan (in SNTS) were ^{241}Am (49.4 ± 1.4 Bq/kg), ^{137}Cs (406.3 ± 1.7 Bq/kg), ^{58}Co (3.2 ± 0.5 Bq/kg), and ^{60}Co (125.9 ± 1.1 and 126.1 ± 1.1 Bq/kg). The present study revealed that dose rates from internal and external exposure around CNPP were not sufficiently low and radiation exposure potency still exists even though current levels are below the public dose limit of 1 mSv/y (ICRP1991). Moreover, parts of the SNTS area may be still contaminated by artificial radionuclides derived from nuclear tests. Long-term follow-up of environmental monitoring around CNPP and SNTS, as well as evaluation of health effects in the population residing around these areas, may contribute to radiation safety with a reduction of unnecessary exposure of residents.

INTRODUCTION

Sixty-five years have passed since the atomic bomb was dropped on Nagasaki on August 9th, 1945. Recently, measurements of plutonium (Pu) isotopes in Nishiyama, an area located 3 km east of the hypocenter, have indicated that in addition to influence from detonation of the Pu nuclear weapon in 1945, the area is also contaminated by global fallout.[1)] According to a 1989 report from the National Institute of Radiological Sciences in Chiba, Japan,[2)] however, the current environmental radiation level (1.0 mSv/y) in Nagasaki was almost as low as background in other areas in Japan.

On April 26th, 1986, the most serious nuclear accident involving radiation exposure in history occurred at the Chernobyl Nuclear Power Plant (CNPP). More than 4,000 thyroid cancer cases were diagnosed during 1986–2002 among those who were children or adolescents (0–17 y) at the time of the Chernobyl accident in Belarus, Ukraine, and the four most contaminated regions of Russia.[3)] Most of the thyroid dose was caused by the intake of iodine-131 (^{131}I) with food during the first weeks after the Chernobyl accident. The shorter-lived radioiodines decay quickly during food-chain transport, and their contribution is estimated to

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have been on the order of 1% of the thyroid dose due to ^{131}I.[4,5] The collective effective dose received during 1986–2005 by ~5 million residents living in affected areas of Belarus, Ukraine and Russia was ~50,000 man Sv with ~40% from ingestion.[6] That contribution might have been larger if countermeasures had not been applied.[6]

Since August 29th, 1949, more than 450 nuclear explosions, including atmospheric, above-ground, and underground tests, have been conducted at the Semipalatinsk Nuclear Testing Site (SNTS). Since the site's closure in 1989, attention has been paid to clarify health effects in the population residing around SNTS. However, since information on radionuclide behavior in the conditions of SNTS is rather sparse, there have been no reports in the literature on parameters of radionuclide transfer to be important contributors to the internal dose to the local population.[7] Thus, due to difficulties in reconstructing exposure doses and establishing a medical screening system, no clear health effects around SNTS have been demonstrated.

The two main pathways leading to radiation exposure to the general public due to "fallout" are external exposure from radionuclides deposited on the ground and internal exposure through ingestion of contaminated foods produced in contaminated areas. It is extremely important to evaluate combined internal and external exposures risks due to the accident at CNPP and nuclear tests at SNTS on public health. However, it is not clear whether chronic exposure with low doses of long-lived radionuclides such as cesium-137 (^{137}Cs) affects human health. For evaluation of current environmental contamination and contributions from internal and external exposure due to artificial radionuclides, therefore, concentrations of radionuclides in edible mushrooms (as a locally produced food), soils and stones as environmental samples from areas around CNPP, in and around SNTS, and in Nagasaki were calculated by gamma spectrometry. Furthermore, annual effective doses were calculated from samples of these areas for estimation of radiation exposure status.

MATERIALS AND METHODS

Sampling places

According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), areas of ^{137}Cs deposition density greater than 555 kBq/m^2 (15 Ci/km^2) are designated as areas of strict control.[8] Sample collections around CNPP were conducted at 1) Minsk city (N53.91, E27.61) approximately 340 km northwest of CNPP in the Republic of Belarus; 2) Gomel city (N52.42, E30.96) 135 km northeast of CNPP in the Republic of Belarus; 3) Korosten city (N50.96, E28.63) approximately 118 km southwest of CNPP in Ukraine; and 4) Klincy city (N53.26, E34.31) approximately 359 km northeast of CNPP in the Russian Federation (Fig. 1). Sample collections around SNTS were conducted at 5) Semipalatinsk city (N50.42, E80.23) and 6) SNTS (N50.69, E79.32) in the Republic of Kazakhstan (Fig. 1). Sample collection in Nagasaki was conducted at 7) Nagasaki (N32.75, E129.87) in Japan (Fig. 1).

Measurement of radionuclides

For evaluation of internal radiation exposure, edible mushrooms harvested from forests, which are known as accumulators of ^{137}Cs, were collected at all sites in 2009. The quantity of mushrooms (wet and/or dry) collected in each area ranged from 45 to 3,005 g. All samples were dried for 24 h at 105°C and were reduced to ashes for 24 h at 450°C before measurement of radionuclide activity. Thermometric programs of the furnace for the ashing protocol were carefully performed because some radionuclides, including cesium, are generally considered to be volatile.

For evaluation of external radiation exposure, undisturbed surface soils (soil depths of 0–5 cm) were collected around CNPP in November 2009, at Semipalatinsk city in February 2010, and Nagasaki in April 2010. For on-site evaluation of environmental contamination near an artificial lake in a crater created by a civil engineering nuclear test on January 15th, 1965 in the eastern part of SNTS, stones were collected in August 2009 around Lake Balapan, at Semipalatinsk city in February 2010, and at Nagasaki in June 2009 (Fig. 2). The quantity of soils and stones collected in each area was between 64 and 4,037 g and between 403 and 1,251 g, respectively. All samples were dried before measurement of radionuclide activity.

After drying, samples were put in plastic containers made of polypropylene and analyzed with a high purity germanium detector (ORTEC®, GEM35, Ortec International Inc., Oak Ridge, TN, USA) coupled to a multi-channel analyzer (MCA7600, Seiko EG&G Co., Ltd., Chiba, Japan) for 80,000 s. Gamma-ray peaks used for measurements were 60 keV for americium-241 (^{241}Am), 605 keV for cesium-134 (^{134}Cs), 662 keV for ^{137}Cs, 811 keV for cobalt-58 (^{58}Co), 1,173 and 1,332 keV for cobalt-60 (^{60}Co), and 1,461 keV for potassium-40 (^{40}K). Decay corrections were made based on sampling date. Detector efficiency calibration for different measurement geometries was performed by use of mixed activity standard volume sources (Japan Radioisotope Association, Tokyo, Japan). The detecting efficiency of this apparatus was 36%. Sample collection, processing and analysis were executed in accordance with standard methods of radioactivity measurement authorized by the Ministry of Education, Culture, Sports, Science and Technology, Japan (http://www.kankyo-hoshano.go.jp/en/index.html). All measurements were performed at Nagasaki Prefectural Institute for Environmental Research and Public Health (Nagasaki, Japan).

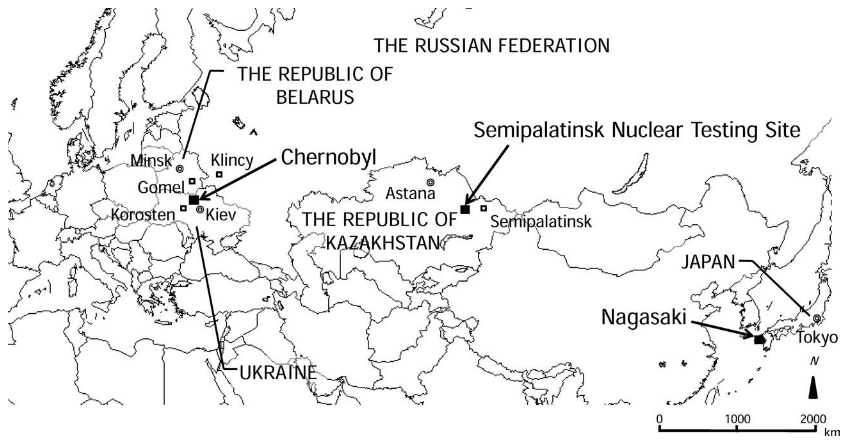

Fig. 1. Areas around Chernobyl Nuclear Power Plant (the Republic of Belarus, Ukraine and the Russian Federation), Semipalatinsk Nuclear Testing Site (the Republic of Kazakhstan), and Nagasaki (Japan).

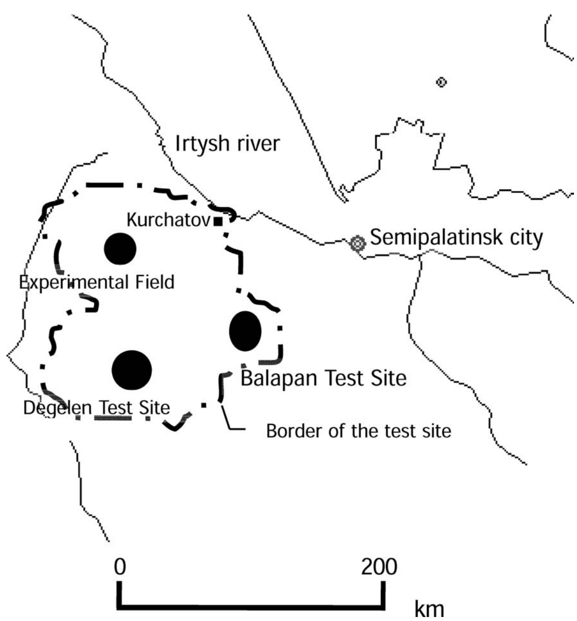

Fig. 2. Balapan Test Site (including Lake Balapan) in the Semipalatinsk Nuclear Testing Site and Semipalatinsk city, the Republic of Kazakhstan.

Effective dose

After measurements, internal effective doses from mushrooms were calculated from ^{137}Cs concentrations with the following formula:

$$H_{int} = C \cdot D_{int} \cdot e$$

where C is the activity concentration of ^{137}Cs (Bq/kg), D_{int} is the dose conversion coefficient for intake of adults (1.3×10^{-5} mSv/Bq for ^{137}Cs, ICRP 1996[9]), and e is the estimated value of annual intake from the latest statistical data issued by the Food and Agriculture Organization of the United Nations (FAO, FAOSTAT 2005, http://faostat.fao.org/default.aspx?alias=faostatclassic) and by the Ministry of Health Labour and Welfare, Japan in 2005 (http://www.mhlw.go.jp/english/index.html). From these reports, annual intakes of mushrooms were estimated at 5.8 kg/year (y) for Belarus, 4.9 kg/y for Ukraine, 7.6 kg/y for Kazakhstan, and 5.9 kg/y for Japan. These values are based on mean values of all subjects (from 1 y to >70 y).

External effective doses from soils were calculated from ^{137}Cs concentration with the following formula:

$$H_{ext} = C \cdot D_{ext} \cdot f \cdot s \cdot a$$

where C is the activity concentration of ^{137}Cs (kBq/m^2), D_{ext} is the dose conversion coefficient as kerma-rate in air at 1 m above ground per unit activity per unit area: 7.6×10^{-4} (μGy/h)/(kBq/m^2) for ^{137}Cs (^{137m}Ba) (with the relaxation mass per unit area (g/cm^2) set to 10 due to passage of more than 20 y since the accident at CNPP in 1986 and the last nuclear test at SNTS in 1989, ICRU 1994[10]), f is the unit conversion coefficient (0.7 Sv/Gy for ^{137}Cs, UNSCEAR 2000[8]), s is the decrease in the coefficient by a shielding factor against exposure with gamma rays from deposit at 1 m above ground (0.7 under the condition of usual land, IAEA-TECDOC-1162[11]), and a is the fixed number in annual value (24 h × 365 d). Since it was the main artificial radionuclide detected in these samples, in the present study ^{137}Cs was considered to be the contributor of radioactivity to mushrooms and soils and as the indicator for calculated effective dose.

RESULTS

Distribution of detected artificial radionuclides and radionuclide ratios (^{137}Cs/^{40}K) of edible mushrooms around CNPP, Semipalatinsk city and Nagasaki are shown in Table 1. ^{137}Cs concentrations were 748.3 ± 3.7 Bq/kg in Minsk city, 2449.6 ± 1.7 Bq/kg in Gomel city, 2635.0 ± 1.2 Bq/kg in Korosten city, 2.8 ± 0.1 Bq/kg in Semipalatinsk city, and 1.7 ± 0.1 Bq/kg in Nagasaki. ^{134}Cs was also detected in Gomel city (0.9 ± 0.1 Bq/kg) and Korosten city (0.8 ± 0.1 Bq/kg). The $^{137}Cs/^{40}K$ ratios from mushrooms were 0.6 in Minsk city, 6.5 in Gomel city and 4.6 in Korosten city, and ratios from Semipalatinsk city and Nagasaki were 0.008 and 0.003, respectively.

Distributions of detected artificial radionuclides in surface soils around CNPP, Semipalatinsk city and Nagasaki are shown in Table 2. The main dose-forming artificial radionuclide from soils around CNPP was ^{137}Cs, and its concentration was 0.9 ± 0.01 kBq/m^2 in Minsk city, 10.4 ± 0.04 kBq/m^2 in Gomel city, 23.0 ± 0.04 kBq/m^2 in Bragin (Gomel oblast), 48.4 ± 0.1 kBq/m^2 in Zhelezniki (Gomel oblast), 19.3 ± 0.05 kBq/m^2 in Korosten city and 69.4 ± 0.08 kBq/m^2 in Klincy city. ^{134}Cs was also detected in Korosten city (0.02 ± 0.006 kBq/m^2). Additionally, ^{241}Am was detected in Klincy city (0.05 ± 0.02 kBq/m^2). The main dose-forming artificial radionuclide of soils in Semipalatinsk city and Nagasaki was ^{137}Cs, and its concentration was 0.1 ±

Table 1. Distribution of detected artificial radionuclides and ^{40}K, and ^{137}Cs (K analog): ^{40}K ratios in mushrooms collected from areas around Chernobyl Nuclear Power Plant (Belarus and Ukraine), Semipalatinsk (Kazakhstan), and Nagasaki (Japan)

	Radionuclide concentration in Bq/kg			Radionuclide ratio
	^{134}Cs	^{137}Cs	^{40}K	$^{137}Cs/^{40}K$
Minsk city	n.d.[a]	748.3 ± 3.7[b]	1246.4 ± 19.4	0.6
Gomel city	0.9 ± 0.1	2449.6 ± 1.7	379.0 ± 2.5	6.5
Korosten city	0.8 ± 0.1	2635.0 ± 1.2	570.6 ± 2.3	4.6
Semipalatinsk city	n.d.	2.8 ± 0.1	333.3 ± 2.1	0.008
Nagasaki	n.d.	1.7 ± 0.1	509.7 ± 2.5	0.003

[a] not detected.
[b] error shows one sigma standard deviation from counting statistics.
Samples were collected at areas around CNPP in May 2009, at Semipalatinsk city in August 2009, and at Nagasaki in March 2009. Radionuclides were analyzed with a germanium-detector coupled to a multi-channel analyzer for 80,000 s at Nagasaki Prefectural Institute for Environmental Research and Public Health, Nagasaki, Japan.

Table 2. Distribution of detected artificial radionuclides and ^{40}K in soils collected at areas around Chernobyl Nuclear Power Plant (Belarus, Ukraine and Russia), Semipalatinsk city (Kazakhstan), and Nagasaki (Japan)

	Radionuclide concentration in kBq/m^2			
	^{241}Am	^{134}Cs	^{137}Cs	^{40}K
Minsk city	n.d.[a]	n.d.	0.9 ± 0.01[b]	6.2 ± 0.1
Gomel city	n.d.	n.d.	10.4 ± 0.04	4.6 ± 0.1
Bragin (Gomel oblast)	n.d.	n.d.	23.0 ± 0.04	1.3 ± 0.04
Zhelezniki (Gomel oblast)	n.d.	n.d.	48.4 ± 0.1	1.2 ± 0.05
Korosten city	n.d.	0.02 ± 0.006	19.3 ± 0.05	2.4 ± 0.08
Klincy city	0.05 ± 0.02	n.d.	69.4 ± 0.08	1.1 ± 0.05
Semipalatinsk city	n.d.	n.d.	0.1 ± 0.01	19.4 ± 0.3
Nagasaki	n.d.	n.d.	0.04 ± 0.01	14.9 ± 0.3

[a] not detected.
[b] error shows one sigma standard deviation from counting statistics.
Samples were collected at areas around CNPP in November 2009, at Semipalatinsk city in February 2010 and Nagasaki in April 2010. Radionuclides were analyzed with a germanium-detector coupled to a multi-channel analyzer for 80,000 s at Nagasaki Prefectural Institute for Environmental Research and Public Health, Nagasaki, Japan.

0.01 kBq/m^2 in Semipalatinsk city and 0.04 ± 0.01 kBq/m^2 in Nagasaki.

Distributions of radionuclides in stones collected beside Lake Balapan in SNTS, Semipalatinsk city and Nagasaki are shown in Table 3. The main dose-forming artificial radionuclides in stones from Lake Balapan were ^{241}Am (49.4 ± 1.4 Bq/kg), ^{137}Cs (406.3 ± 1.7 Bq/kg), ^{58}Co (3.2 ± 0.5 Bq/kg), and ^{60}Co (125.9 ± 1.1 and 126.1 ± 1.1 Bq/kg). No artificial radionuclides were detected in stones from either Semipalatinsk city or Nagasaki.

Internal and external effective doses from ^{137}Cs and effective dose ratios around CNPP, Semipalatinsk city and Nagasaki are summarized in Table 4. Calculated internal effective ^{137}Cs doses due to ingestion of mushrooms were

Table 3. Distribution of detected artificial radionuclides and ^{40}K in stones collected beside Lake Balapan within the Semipalatinsk Nuclear Testing Site, Semipalatinsk city (Kazakhstan), and Nagasaki (Japan)

	Radionuclide concentration in Bq/kg					
	^{241}Am	^{134}Cs	^{137}Cs	^{58}Co	^{60}Co	^{40}K
Lake Balapan (SNTS)	49.4 ± 1.4[a]	n.d.[b]	406.3 ± 1.7	3.2 ± 0.5	125.9 ± 1.1 126.1 ± 1.1	302.6 ± 5.7
Semipalatinsk city	n.d.	n.d.	n.d.	n.d.	n.d.	663.1 ± 9.9
Nagasaki	n.d.	n.d.	n.d.	n.d.	n.d.	484.8 ± 7.3

[a] error shows one sigma standard deviation from counting statistics.
[b] not detected.
Samples were collected at SNTS in August 2009, at Semipalatinsk city in February 2010, and at Nagasaki in June 2009. Radionuclides were analyzed with a germanium-detector coupled to a multi-channel analyzer for 80,000 s at Nagasaki Prefectural Institute for Environmental Research and Public Health, Nagasaki, Japan.

Table 4. Internal and external effective doses from ^{137}Cs and effective dose ratios to ^{137}Cs in areas around Chernobyl Nuclear Power Plant (Belarus, Ukraine and Russia), Semipalatinsk city (Kazakhstan), and Nagasaki (Japan)

	Internal effective dose in mSv/y*	External effective dose in mSv/y†	Effective dose in mSv/y‡	Effective dose ratio (H_{int}/H_{ext})§
Minsk city	5.6×10^{-2}	2.9×10^{-3}	5.9×10^{-2}	19.3
Gomel city	1.8×10^{-1}	3.4×10^{-2}	2.1×10^{-1}	5.3
Bragin (Gomel oblast)	not available	7.4×10^{-2}	$> 7.4 \times 10^{-2}$	–
Zhelezniki (Gomel oblast)	not available	1.6×10^{-1}	$> 1.6 \times 10^{-1}$	–
Korosten city	1.7×10^{-1}	6.2×10^{-2}	2.3×10^{-1}	2.7
Klincy city	not available	2.2×10^{-1}	$> 2.2 \times 10^{-1}$	–
Semipalatinsk city	2.8×10^{-4}	2.0×10^{-4}	4.8×10^{-4}	1.4
Nagasaki	1.3×10^{-4}	1.3×10^{-4}	2.6×10^{-4}	1.0

* Internal effective doses from ^{137}Cs were calculated with the following formula: $H_{int} = C \cdot D_{int} \cdot e$.
where C is the activity concentration of ^{137}Cs (Bq/kg), D_{int} is the dose conversion coefficient for intake of adults (1.3×10^{-5} mSv/Bq for ^{137}Cs, ICRP 1996), and e is the estimated value of annual intake from the latest statistical data from FAO (FAOSTAT, 2005) and the Ministry of Health Labour and Welfare, Japan in 2005 (5.8 kg/y for Belarus, 4.9 kg/y for Ukraine, 7.6 kg/y for Kazakhstan and 5.9 kg/y for Japan).
† External effective doses were calculated with the following formula: $H_{ext} = C \cdot D_{ext} \cdot f \cdot s \cdot a$.
where C is the activity concentration of ^{137}Cs (Bq/m^2), D_{ext} is the dose conversion coefficient as kerma-rate in air at 1 m above ground per unit activity per unit area (7.6×10^{-4} (μGy/h)/(kBq/m^2) for ^{137}Cs (^{137m}Ba) with the value of relaxation mass per unit area 10 g/cm^2 (ICRU 1994)), f is the unit conversion coefficient (0.7 Sv/Gy for ^{137}Cs (UNSCEAR 2000)), s is the decrease in the coefficient by a shielding factor against exposure with gamma rays from deposit at 1 m above ground (0.7 under the condition of usual land, IAEA-TECDOC-1162), and a is the fixed number in annual value (24 h × 365 d).
‡ Effective dose was calculated as the sum of internal effective dose and external effective dose.
§ Effective dose ratio was described as internal effective dose over external effective dose.

5.6×10^{-2} mSv/y in Minsk city, 1.8×10^{-1} mSv/y in Gomel city, 1.7×10^{-1} mSv/y in Korosten city, 2.8×10^{-4} mSv/y in Semipalatinsk city and 1.3×10^{-4} mSv/y in Nagasaki. Calculated external effective doses of ^{137}Cs were 2.9×10^{-3} mSv/y in Minsk city, 3.4×10^{-2} mSv/y in Gomel city, 7.4×10^{-2} mSv/y in Bragin, 1.6×10^{-1} mSv/y in Zhelezniki, 6.2×10^{-2} mSv/y in Korosten city, 2.2×10^{-1} mSv/y in Klincy city, 2.0×10^{-4} mSv/y in Semipalatinsk city and 1.3×10^{-4} mSv/y in Nagasaki. Therefore, effective doses by area were 5.9×10^{-2} mSv/y in Minsk city, 2.1×10^{-1} mSv/y in Gomel city, 2.3×10^{-1} mSv/y in Korosten city, 4.8×10^{-4} mSv/y in Semipalatinsk city and 2.6×10^{-4} mSv/y in Nagasaki. Effective doses from Gomel city and Korosten city were comparatively high compared with those from Minsk city, Semipalatinsk city, and Nagasaki. Effective dose ratios around CNPP were 19.3 in Minsk city, 5.3 in Gomel city and 2.7 in Korosten, respectively. On the other hand, effective dose ratios from Semipalatinsk city and Nagasaki were 1.4 and 1.0, respectively.

DISCUSSION

In the first 10 y after the Chernobyl accident, a very large fraction of the total expected dose from consumption of contaminated agricultural products had already been delivered, and only a small contribution was expected to be delivered 20 y after the accident.[12] In the present study, it was confirmed that artificial radionuclides, mainly ^{137}Cs, derived from the accident at CNPP in 1986 remain to this day. However, current radiation exposure through consumption of locally produced food may be small in both Semipalatinsk city and in Nagasaki.

Mushrooms produced around CNPP contained detectable ^{137}Cs. In the fungi soil system Cs is considered a potassium analog and is expected to behave like potassium. This is because the elements are chemically similar and because potassium availability affects uptake and distribution of ^{137}Cs.[13,14] In the present study, it was confirmed that edible mushrooms around CNPP—especially in Gomel city and Korosten city, where concentrations of ^{137}Cs were high compared to these of Semipalatinsk and Nagasaki—selectively took in ^{137}Cs instead of potassium (^{40}K). ^{137}Cs is taken into the human body through respiration and ingestion of food products such as mushrooms. It has been reported that chronic exposure with low doses of ^{137}Cs during postnatal development can affect mineral homeostasis and vitamin D metabolism.[15,16] Since 1991, cases of radiocontamination have been reported including an increase of radioactive foodstuffs (including mushrooms) and human contamination in the Bryansk-Gomel Spot on the Russian-Belarussian border.[17] Although unnecessary radiophobia in the general population should be avoided, careful follow-up of children living around CNPP is needed.

It has been reported that Klincy city was contaminated with ^{137}Cs-deposition densities of >37 kBq/m^2.[12] Although contamination of soil in Klincy city has been decreasing since the Chernobyl accident, the present study confirmed that areas around CNPP, especially the Russian-Belarussian border including Klincy city and Gomel oblast, are still contaminated.

Furthermore, radiation dose rates were evaluated beside Lake Balapan and at Semipalatinsk city, and environmental radioactivity levels in stones collected beside Lake Balapan and Semipalatinsk city were found to be quite different. According to some reports, the fission products such as Pu and the neutron induced radioactivity were detected from the soil samples in SNTS. Some of the detected isotopes, europium-152 (^{152}Eu), europium-154 (^{154}Eu), ^{60}Co and bismuth-217 (^{217}Bi), were estimated to have been produced from the stable isotopes in the ground soil, which were activated by the neutron induced reaction at the bomb explosion.[18] Thus, this result suggests that a certain part of the SNTS area may be still contaminated by plural artificial radionuclides derived from nuclear tests. It also suggests that radionuclides derived from fallout from above ground nuclear tests in SNTS have indirectly affected the environment of vast areas, including Semipalatinsk city.

According to an International Atomic Energy Agency report (IAEA, 2006), external doses around CNPP during 1986–2005 were about 1.2 times higher, and internal doses were about 1.1–1.5 times higher than those obtained during 1986–1995 (depending on soil properties and applied countermeasures).[6] The dose rate from internal radiation of a rural Bryansk population decreased more slowly than the dose rate from external radiation, and also showed an irregular time variation.[19] Radionuclides are generally transported by adhesion to aerosol or soil particles, and seasonal dependence on atmospheric transport is likely to play a crucial role in transporting ^{137}Cs from CNPP.[20] Because 20 y or more have passed after the abovementioned nuclear disasters and the behavior of radionuclides depends on climate changes, radionuclide analysis of environmental samples is extremely practical for evaluation of radiation exposure risk. In the present study, effective dose ratios were different between Chernobyl, Semipalatinsk and Nagasaki, all of which have been affected by radiation disasters. Current environmental contamination and contributions from internal and external exposure due to the Chernobyl accident and nuclear tests at SNTS were simultaneously evaluated in these areas.

There were several limitations in this study. The internal effective doses of Bragin, Zhelezniki and Klincy city could not be evaluated, since sufficient amounts of samples from these areas could not be obtained. Moreover, several radionuclides could not be analyzed by an extraction procedure, including strontium-90 (^{90}Sr). Different cultivation methods, eating habits of mushrooms in sampling places and homogenized soils in extensive areas could not be standardized.

The intake of radionuclides such as ^{137}Cs also varies by cooking method or eating habit. It is necessary to calculate effective doses with detailed conditions. To this end, in the present study, internal exposure risks were evaluated through edible mushrooms which the inhabitants in each area consumed daily. ^{137}Cs was selected as it was frequently detected in the environment as a target artificial radionuclide and was used to evaluate radiation exposure risks. In the present study, consumption of mushrooms was estimated from several statistical datasets, as there were no detailed data concerning the consumption of mushrooms on each site. Daily intake by adults of mushrooms has been reported to be 28 g/d/person in Bryansk region, approximately 200 km northeast of CNPP in the Russian Federation in 1994, and was reported to be 11 g/d/person in the Japanese population in 2000.[21,22] Previously, the ^{137}Cs body burden was evaluated in the inhabitants of Bryansk oblast, Russian Federation, from 1998 to 2008 in order to determine the current health risk of internal radiation exposure in inhabitants residing in this area by a whole-body counter (WBC). ^{137}Cs concentration was significantly higher in the late period and showed seasonal variation, suggesting that inhabitants may have consumed contaminated forest products such as mushrooms.[23] The ^{137}Cs concentration decreased gradually from 1998 to 2003, increased in 2004 and was statistically higher in autumn than other seasons every year after 2004.[23] Moreover, the calculated annual internal exposure doses during 1998 to 2008 were between 0.06 and 0.11 mSv/y (median).[23] In the present study, calculated internal effective doses around CNPP (Minsk city, Gomel city and Korosten city) were between 0.06 and 0.18 mSv/y. It is suggested that the internal exposure estimation of the environmental samples such as mushrooms by gamma spectrometry may be appropriate as well as the calculated internal exposure doses by WBC. According to another report, was also a statistically significant relationship between ^{137}Cs specific activity and the contamination level in the settlement of Bryansk oblast from 1991 to 1996.[24] Because radionuclides in soils may be unequally distributed around CNPP and SNTS, further investigation is needed.

In conclusion, even though estimated internal and external radiation doses from ^{137}Cs around CNPP were below the public dose limit (1 mSv/y), radiation exposure potency still exists around CNPP. Moreover, Lake Balapan in SNTS may remain contaminated by artificial radionuclides derived from nuclear tests. Long-term follow-up of environmental monitoring around CNPP and SNTS, as well as evaluation of health effects in the population residing around these areas, could contribute to radiation safety and reduce unnecessary exposure to residents.

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