Chapter 14
Dose Estimation of External and Internal Exposure in Japanese Macaques After the Fukushima Nuclear Power Plant Accident

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Abstract Cumulative dose of external and internal exposures following the Fukushima Daiichi Nuclear Power Plant (FNPP) accident was estimated for Japanese macaques (*Macaca fuscata*) around FNPP. Conversion factors for Japanese macaques modeled as ellipsoids were estimated for external exposure from contaminated ground and internal exposure uniformly distributed in the body. Conversion factors for seven radionuclides, namely, tellurium-129 (^{129}Te), ^{129m}Te, iodine-131 (^{131}I), ^{132}Te, ^{132}I, cesium-134 (^{134}Cs) and ^{137}Cs were calculated using the PHITS code. The estimated factors for the seven radionuclides were consistent with those in ICRP Publication 108, using an effective radius for comparison. The external, internal and total exposures for 13 macaques in Namie Town were estimated by applying the calculated factors. The estimated cumulative exposures for the periods from the accident occurred to the sampling date, ranged from 0.26 to 1.6 Gy. The average exposure was 0.64 Gy in averaged over the 11 sampled macaques except for the 2 macaques which might be born after the FNPP accident.

Keyword Fukushima Daiichi Nuclear Power Plant accident · Dose rate conversion factor · External exposure · Internal exposure · Japanese macaques

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14.1 Introduction

The nuclear accident at the Fukushima Daiichi Nuclear Power Plant (FNPP) was triggered by an enormous earthquake and associated tsunami (the Great East Japan Earthquake) on March 11, 2011. A large quantity of radioactive nuclides were released, resulting in the severe contamination of a wide area of the southern Tohoku region to the northern Kanto region. The main depositions occurred on March 15 and March 20–21, 2011 [1, 2].

Since the accident, many studies have examined the effect of radiation on animals, insects and plants [3–8]. However, cumulative exposure in animals is quite difficult to estimate because it is challenging to account for habitat and behavioral properties. Estimates of exposure could be improved using a contamination map combined with habitat information. Dose rate and its temporal changes can be estimated for target animals in an area from the contamination map.

The National Nuclear Security Administration (NNSA) performed a rapid survey of radiation and contamination on March 17–19, 2011 using the Aerial Measuring System. These data were used for the initial NNSA March 22, 2011, report and are available for independent analysis [9]. Additionally, the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT), conducted a contamination study using a 2-km mesh from June to August 2011 [10]. This study started 3 months after the main deposition on March 15, 2011. The radionuclides with short half-lives already decayed away; however, ^{134}Cs and ^{137}Cs remained over a wide area around FNPP.

Studies of the biological effect of radiation following the FNPP accident were initiated by Tohoku University as a part of a Comprehensive Dose Evaluation Project Concerning Animals Affected by The Fukushima Daiichi Nuclear Power Plant Accident and a Nuclear Energy Science and Technology and Human Resource Development Project by MEXT using Japanese macaques (*Macaca fuscata*) sampled in the Fukushima area. Macaques, like humans, belong to the order, Primates. Therefore, the biological effect on macaques might provide important information that can be applied to humans. To estimate exposure, the International Commission of Radiological Protection (ICRP) summarized conversion factors for reference animals under internal exposure to uniformly distributed radionuclides and external exposure to contaminated ground with bodies simulated as ellipsoids in ICRP Publication 108 [11]. The factors are available for 75 radionuclides from ICRP Publication 108. However, the Japanese macaque is not one of the ICRP reference animals. Therefore, we estimated the appropriate conversion factors for the species using the Monte Carlo technique.

14.2 Materials and Methods

14.2.1 ^{137}Cs Contamination Map

NNSA [9] and MEXT data [10] for ^{137}Cs contamination were combined and interpolated by the Universal Kriging method using System for Automated Geoscientific Analyses–Geographic Information System (SAGA–GIS) software [12]. A variogram was generated, which describes the variance of the difference between ^{137}Cs concentrations at two locations fitted by a quartic function, using SAGA-GIS [10]. The reproducibility of the variogram was 95% within 70 km from FNPP. The interpolated values were stored in 1,814 × 1,854 meshes for latitudes from 36.51611 to 38.32911 and longitudes from 139.30506 to 141.15896. The interpolated map is shown in Fig. 14.1. Using this map, ^{137}Cs contamination at the coordinates where macaques were sampled can be calculated.

14.2.2 Ellipsoid Model

In ICRP Publication 108, the reference animals in terrestrial conditions are modeled as various ellipsoids [11], as listed in Table 14.1. Therefore, Japanese macaques were also modeled as ellipsoids with a density of 1 g/cm^3 according to ICRP Publication 108 assumption. Japanese macaques were categorized into three groups

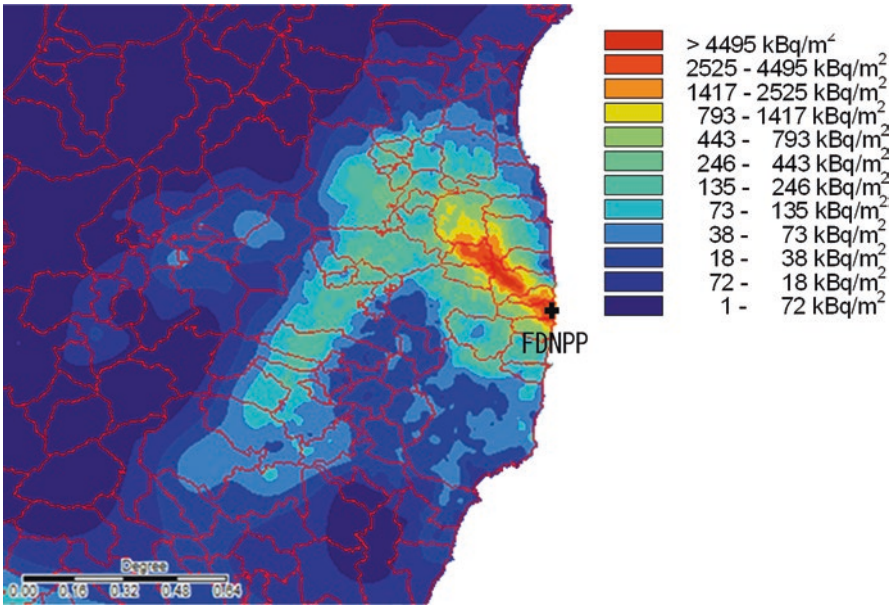


Fig. 14.1 Kriging interpolated map for the combined NNSA and MEXT data

Table 14.1 Body parameters for the reference animals in ICRP Publication 108 [11] and the calculated effective radius

Reference animal	Body mass (kg)	Body shape proportions (ellipsoid)	Effective radius (cm)
Deer	245	1 × 0.4620 × 0.4620	38.7
Rat	0.314	1 × 0.3000 × 0.2500	4.21
Duck egg	5.03×10^{-2}	1 × 0.6670 × 0.6670	2.29
Duck	1.26	1 × 0.3330 × 0.2670	6.69
Frog egg	5.24×10^{-4}	1 × 1 × 1	0.500
Frog	0.0314	1 × 0.375 × 0.313	1.96
Bee colony	28.3	1 × 0.500 × 0.500	18.8
Bee	5.89×10^{-4}	1 × 0.375 × 0.375	0.520
Earthworm	5.24×10^{-3}	1 × 0.100 × 0.100	1.08

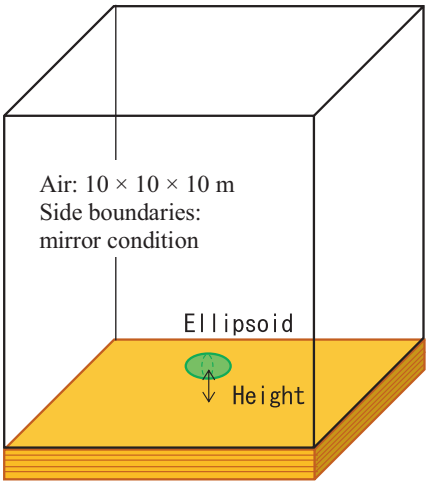
Table 14.2 Japanese macaque models for the walk and sit postures based on physical measurements

	Walk model			Sit model		
Axis (cm)	<5 kg (S)	5–10 kg (M)	>10 kg (L)	<5 kg (S)	5–10 kg (M)	>10 kg (L)
Major	15	25	30	15	25	30
First minor	6.2	9.7	12	6.2	9.7	12
Second minor	4.1	6.4	8	4.1	6.4	8
Height	20	30	40	–	–	–

according to the body size, namely, small (S), middle (M) and large (L), with the weight of less than 5 kg, 5–10 kg and greater than 10 kg, corresponding to the sampled macaques. The ellipsoid dimensions were based on the physical measurements of 52 macaques obtained by Tohoku University and the values are listed in Table 14.2. Two types of postures, the walk and sit postures, were considered and are also listed in Table 14.2.

14.2.3 Conversion Factor Calculation

The conversion factors for internal exposure to uniformly distributed radionuclides in an ellipsoid and external exposure to uniformly contaminated ground from 0 to 0.5 cm were calculated using PHITS code [13]. The calculation geometry of air occupying a 10 × 10 × 10 m area and 50-cm-deep ground soil was taken into account. The ellipsoid macaque was set at the center of the ground surface. To minimize calculation time, the four side boundaries were set to a mirror condition. Gamma-rays and β-particles were separately calculated for seven radionuclides, namely, ^{129}Te, ^{129m}Te, ^{131}I, ^{132}Te, ^{132}I, ^{134}Cs and ^{137}Cs. The γ-ray energies and emission rates for the radionuclides were obtained from the National Nuclear Data Center [14]. Beta-particle energy spectra were obtained from the literature [15, 16], and the internal conversion electrons for each radionuclide were obtained from the website of the National Nuclear Data Center [14]. The energy deposition in the ellipsoids was calculated for each γ-ray and each electron source. In addition, to consider the



Soil layer: 0-0.5 cm, 0.5-1 cm, 1-2 cm, 2–5 cm, 5–10 cm, 10–15 cm, and 15–20 cm.

Fig. 14.2 Calculation geometry for PHITS

depth profile of radionuclides, the deposition energy in the walk model for body size L was also calculated for sources uniformly distributed in six soil layers, namely, 0.5–1 cm, 1–2 cm, 2–5 cm, 5–10 cm, 10–15 cm and 15–20 cm (Fig. 14.2).

The external exposure conversion factors were derived by weighing each deposition energy for the depth profile of the radionuclide. The factor D_i^{ex} ((mGy/day)/(Bq/m^2)) of the *i*th radionuclide from depth layer d_k is expressed by

$$D_i^{ex}\left(d_k\right) = \sum_{j=\gamma,\beta} \frac{E_{ij}\left(d_k\right)}{m} I_J S \cdot 3600 \cdot 24 \cdot 1000, \tag{14.1}$$

where subscript *j* indicates emitted γ-rays or β-particles, I_j is the emission rate for emitted γ-rays or β-particles, *m* is the mass of the macaque-simulating ellipsoid, *E* is the deposition energy in the ellipsoid by emitted γ-rays and β-particles and *S* is the calculated area expressed in m^2. In the case of soil surface contamination, similar to the ICRP Publication 108 assumption, the depth layer d_1 is only 0–0.5 cm. To estimate the factor for the depth profile of radionuclides, the fraction of radionuclides as a function of depth, $f(d_k)$, is introduced and summed for seven layers:

$$D_i^{ex} = \sum_{7}^{k=1} f_1\left(d_k\right) \cdot D_i^{ex}\left(d_k\right) \tag{14.2}$$

The internal exposure conversion factor D_i^{in} ((mGy/d)/(Bq/kg)) for each radionuclide *i* was calculated using each deposition energy as follows:

$$D_i^{in} = \sum_{j=\gamma,\beta} \frac{E_{ij}}{m} I_j m \cdot 3600 \cdot 24 \cdot 1000. \tag{14.3}$$

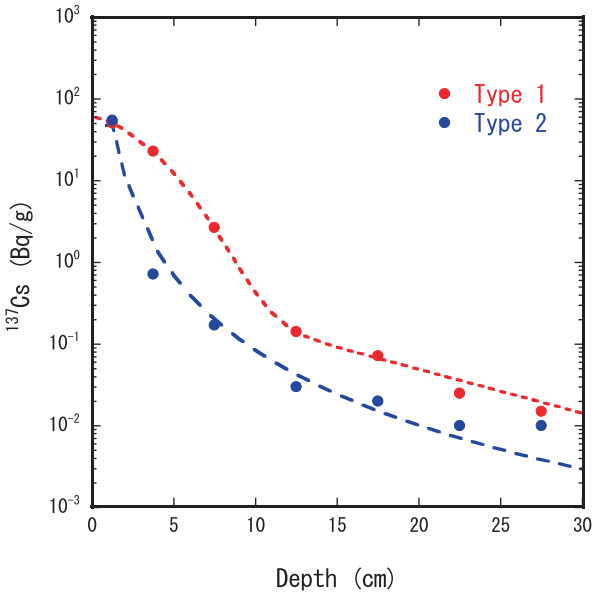


Fig. 14.3 Tested depth profiles. Type 1, farmland; Type 2, normal land

14.2.4 Depth Profile

There is a lack of depth profile data, except for radioactive Cs. The depth profiles of ^{137}Cs radioactivity have been measured at various locations [17–20]. The relaxation mass depths of ^{137}Cs have been reported as time-dependent values of 1.1–1.5 g/cm^2 for the period from December 2012 to December 2013 [17]; 0.9 g/cm^2 for soil with a low clay content [18]; 1.56 g/cm^2, on average, for paddy soil [19]; and 1.04, 1.38, 1.05 and 1.29 g/cm^2 in April 2011, October 2011, December 2011 and March 2012, respectively [20]. The conversion factor for the ^{137}Cs depth-profiled soil was calculated using the relaxation mass depths from 0.5 to 2.7 according to Eq. (14.2). Additionally, the typical depth profiles for our measurement, as shown in Fig. 14.3, were tested.

14.3 Results and Discussion

14.3.1 Conversion Factor

The calculated conversion factors for the surface layer for seven radionuclides are listed in Table 14.3. The external exposure results for the walk model and the internal exposure results were compared with those in ICRP Publication 108 against the effective radius and are shown in Fig. 14.4. The calculated factor and those of ICRP Publication 108 agree within 20%. Therefore, if we allow for 20% uncertainty, the conversion factor in ICRP Publication 108 for the effective radius can be used.

Table 14.3 Estimated conversion factors for the external exposure rates of the walk and sit model for surface contamination and the internal exposure rate

Radionuclide	Body group	Conversion factor [(mGy/d)/(Bq/m^2)] External, walk model	Conversion factor [(mGy/d)/(Bq/m^2)] External, sit model	Conversion factor [(mGy/d)/(Bq/kg)] Internal
^{134}Cs	L	9.50×10^{-5}	1.00×10^{-4}	7.63×10^{-3}
	M	1.02×10^{-4}	1.07×10^{-4}	6.72×10^{-3}
	S	1.17×10^{-4}	1.16×10^{-4}	5.14×10^{-3}
^{137}Cs	L	3.53×10^{-5}	3.77×10^{-5}	4.91×10^{-3}
	M	3.81×10^{-5}	3.93×10^{-5}	4.58×10^{-3}
	S	4.32×10^{-5}	4.31×10^{-5}	4.01×10^{-3}
^{132}I	L	1.17×10^{-4}	1.22×10^{-4}	9.87×10^{-3}
	M	1.24×10^{-4}	1.33×10^{-4}	9.27×10^{-3}
	S	1.46×10^{-4}	1.44×10^{-4}	8.25×10^{-3}
^{131}I	L	2.23×10^{-5}	2.21×10^{-5}	5.02×10^{-3}
	M	2.40×10^{-5}	2.35×10^{-5}	4.60×10^{-3}
	S	2.75×10^{-5}	2.60×10^{-5}	3.88×10^{-3}
^{132}Te	L	1.18×10^{-5}	9.95×10^{-6}	3.57×10^{-3}
	M	1.29×10^{-5}	1.08×10^{-5}	3.15×10^{-3}
	S	1.45×10^{-5}	1.18×10^{-5}	2.43×10^{-3}
^{129m}Te	L	3.26×10^{-6}	3.09×10^{-6}	7.86×10^{-3}
	M	4.20×10^{-6}	3.68×10^{-6}	7.83×10^{-3}
	S	5.81×10^{-6}	5.20×10^{-6}	7.77×10^{-3}
^{129}Te	L	6.34×10^{-6}	5.55×10^{-6}	6.48×10^{-3}
	M	7.48×10^{-6}	6.50×10^{-6}	6.43×10^{-3}
	S	1.18×10^{-5}	9.58×10^{-6}	6.34×10^{-3}

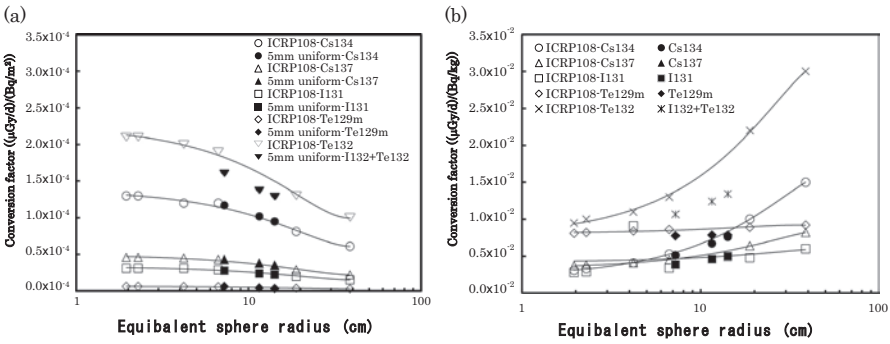


Fig. 14.4 (**a**) External exposure for the walk model and (**b**) internal exposure for the Japanese macaque. Values were compared with those in ICRP Publication 108 against the effective radius

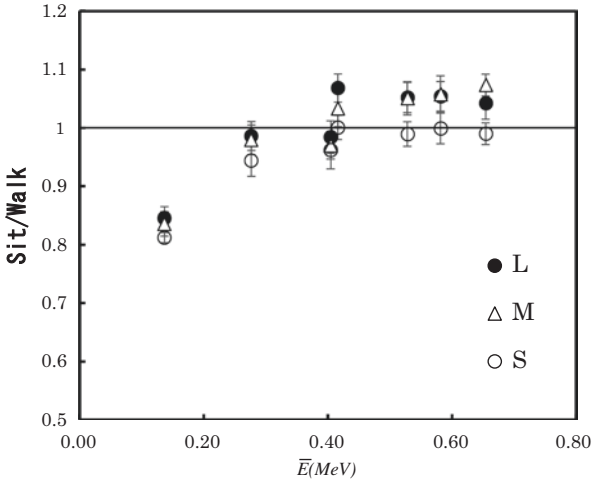


Fig. 14.5 Conversion factor ratio of the walk-to-sit model as a function of $\bar{E}$

The conversion factor ratio of external exposure for the walk to the sit model is plotted as a function of $\bar{E}$, which is defined as the sum of mean γ-ray and β-particle energies, in Fig. 14.5. The ratio is consistent with unity within statistical uncertainty, except for the lowest $\bar{E}$ of ^{132}Te. The ratio for ^{132}Te, which emits low-energy γ-rays and β-particles, is approximately 0.83. This is due to the shielding effect by an individual's own body. Therefore, except for low-energy β-particles and γ-rays, the conversion factors for both the walk model and sit model are approximately equal.

14.3.2 Conversion Factor for Depth-Profiled Radionuclides

The conversion factors for the seven depth-profiled radionuclides with a relaxation depth from 0.6 to 2.6 and measured depth profiles of ^{134}Cs and ^{137}Cs in Iitate Village, Fukushima Prefecture, in comparison with the 0–0.5 cm uniform factor are shown in Fig. 14.6a, b, respectively. The relaxation depths of ^{137}Cs radioactivity from previous studies [17–20] are shown in light red and ranged from 0.9 to 1.5 g/cm^2. A soil self-shielding factor introduced as a ratio of the conversion factor for the depth profiles to that for the uniformly distributed factor in surface soil characterized by the relaxation depth is summarized in Table 14.4. The soil self-shielding factors for ^{134}Cs and ^{137}Cs were 0.74 and 0.71, respectively. The shielding factor for Type 1 for the slowest measured depth profiles for farmland in Fig. 14.6b was less than that for a relaxation depth of 2.6 g/cm^2. However, the shielding factor for Type 2 for the typical depth profile for undisturbed land is consistent with those for the relaxation depth of 0.9–1.5 g/cm^2. The variation within the range of 0.9–1.5 g/cm^2 corresponds to the variation in the conversion factor for ^{134}Cs or ^{137}Cs, which was less than 8%.

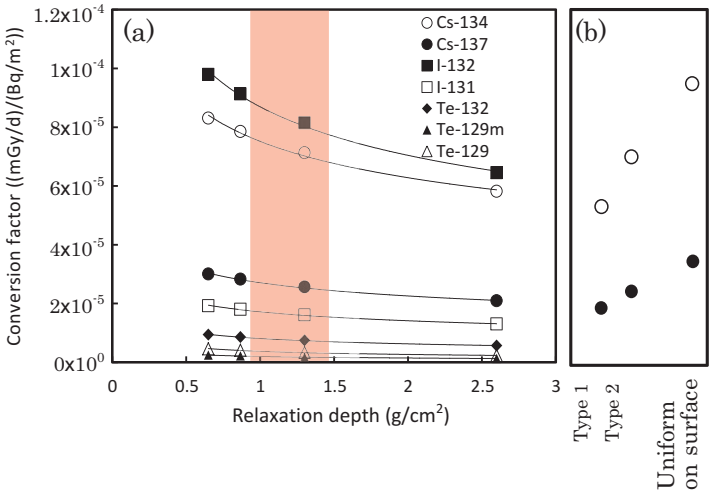


Fig. 14.6 (**a**) Calculated conversion factors of walk model for seven radionuclides of relaxation depth and (**b**) typical measured depth profiles

Table 14.4 Soil self-shielding factor for seven radionuclides

Radionuclide	Soil shielding factor
^{134}Cs	0.74
^{137}Cs	0.71
^{132}I	0.68
^{131}I	0.71
^{132}Te	0.62
^{129m}Te	0.54
^{129}Te	0.52

14.3.3 Example of External Exposure Estimation

To consider cumulative exposure to soil contamination, temporal changes in the air dose from radionuclides deposited on the ground are good references. The air dose rate from seven radionuclides from radioactivity concentrations was estimated around FNPP in 2011 [9, 10]. The air dose rate changes were estimated for several locations. For example, the estimated dose rate change in Iitate Village assuming only the physical half-life [2] is shown in Fig. 14.7. Integrating over time, the cumulative air dose can be estimated. The cumulative air dose normalized by the dose at 200 years after deposition and the radionuclide contribution as a function of time are shown in Fig. 14.8a, b, respectively. The sum of the ^{134}Cs and ^{137}Cs contributions to the cumulative air dose at 1 year after deposition or later exceeds 90%. In the sampled macaques, exposure is expected to be the same as the contributions to the air dose. Accordingly, the external exposure for some samples after 1 year following the FNPP accident can be estimated by only radioactive ^{134}Cs and ^{137}Cs, neglecting the 10% contribution of external exposure to other radionuclides.

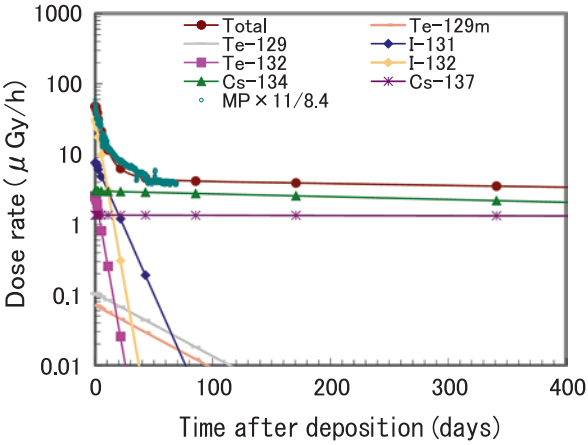


Fig. 14.7 Estimated dose rate change in Iitate Village assuming only the physical half-life

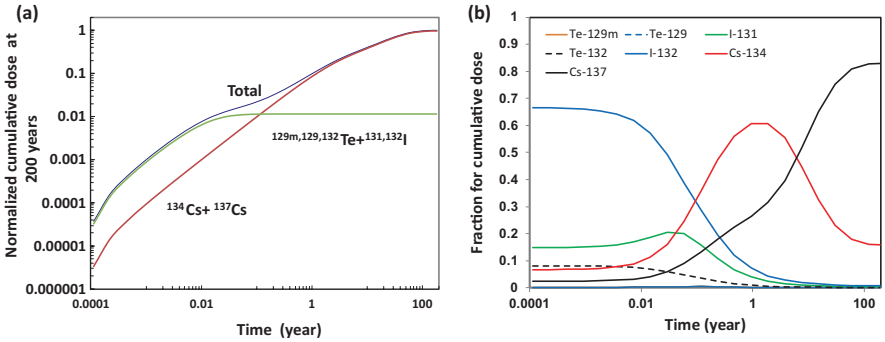


Fig. 14.8 (**a**) Cumulative dose in Japanese macaques against time since deposition normalized by the dose at 200 years; (**b**) radionuclide contribution as a function of time

Using the ^{134}Cs and ^{137}Cs conversion factors for the walk model, the external, the internal and the total exposures were calculated for the sampled macaques at Namie Town, Fukushima Prefecture, in 2013. Only ^{137}Cs concentration and ^{134}Cs concentration, which is the same as ^{137}Cs concentration in March 2011, were used in this estimation. The ground concentration of ^{137}Cs (interpolated values in Fig. 14.1) and the ^{137}Cs concentration in macaque bodies measured at Tohoku University [21] were used in this calculation. To account for the effect of the depth profile, the soil self-shielding factor of the depth profile for a relaxation depth of 1.3 g/cm^2 was assumed to be 0.74 for ^{134}Cs and 0.71 for ^{137}Cs. The macaques were caught in 2013 or later; therefore, only exposure to ^{134}Cs and ^{137}Cs was taken into account. Additionally, the ratio of the accumulated concentration of ^{134}Cs to ^{137}Cs was assumed to be unity. The estimated total exposures ranged from 0.26 to 1.6 Gy, as shown in Table 14.5. Two sampled macaques showed the body weight less than 2kg. There is a possibility that these 2 macaques were born after the FNPP accident. The average exposure was 0.64 Gy in averaged over the 11 sampled macaques except for the 2 macaques.

Table 14.5 Summary of results for a sample of Japanese macaques in Namie Town. $\dot{D}$ and D show the exposure rates and cumulative exposure. $t = 0$ indicates the values at the time of deposition

ID	Latitude	Longitude	Sampling date	Days from accident	Body length (cm)	Weight (kg)	^{137}Cs accumulation in soil (kBq/m^2)	^{137}Cs in the body (Bq/kg)	^{137}Cs $\dot{D}_{in}$ ($t = 0$) (μGy/day)	^{134}Cs $\dot{D}_{in}$ ($t = 0$) (μGy/day)	D_{in} (mGy)	^{137}Cs $\dot{D}_{ex}$ ($t = 0$) × 0.71 (μGy/day)	^{134}Cs $\dot{D}_{ex}$ ($t = 0$) × 0.74 (μGy/day)	D_{ex} (mGy)	Total dose (mGy)
7	37.55924	140.7524	2013/3/6	726	80	–	2105	35,834	184.3	286.1	282	52.8	148.0	116	398
64	37.54273	140.8626	2013/10/28	962	50	5.8	3026	26,238	127.9	187.5	241	81.9	228.0	224	465
217	37.54179	140.8619	2013/11/8	973	45	4.7	3151	10,654	47.3	60.5	122	96.6	272.9	373	495
221	37.49008	140.9414	2015/7/10	1582	66.5	15.6	1467	6921	37.8	58.6	110	36.8	103.1	146	255
233	37.50656	140.9104	2015/9/28	1662	60	12	2349	4730	25.9	40.3	78	58.9	165.1	240	318
252	37.49175	140.9326	2015/12/15	1740	60	11.9	2139	11,760	64.9	100.7	202	53.6	150.3	227	429
404	37.47923	140.9886	2016/3/24	1840	49	–	6657	33,742	189.1	293.4	640	16.7	46.8	76	716
405	37.54214	140.8606	2016/11/22	2083	52	9.5	3412	65,323	341.5	500.8	1131	92.4	257.1	419	1550
406[a]	37.54214	140.8606	2016/11/22	2083	32	2	3412	31,550	144.5	184.9	454	104.6	295.5	478	932
413	37.54121	140.8628	2016/12/2	2093	60	13	3115	65,581	367.8	570.8	1251	78.1	218.9	356	1608
414[a]	37.51081	140.8954	2016/12/2	2093	31	1.4	2119	4791	22.0	28.1	69	65.0	183.5	298	367
477	37.47565	140.9402	2017/12/8	2464	47	9.5	2610	2012	10.8	15.8	40	70.7	196.7	353	393
478	37.47231	140.9399	2017/12/12	2468	46	8.5	2993	1816	9.7	14.3	36	81.0	225.6	405	441

[a]There is a possibility that the 2 macaques were born after the FNPP accident

14.4 Conclusions

The cumulative external and internal exposures attributed to the FNPP accident were estimated for Japanese macaques around FNPP. Conversion factors for Japanese macaques, modeled as ellipsoids, for external exposure from contaminated ground and internal exposure uniformly distributed in the body were calculated. The estimated conversion factors for seven radionuclides, namely, ^{129}Te, ^{129m}Te, ^{131}I, ^{132}Te, ^{132}I, ^{134}Cs and ^{137}Cs, agreed within 20% with those in ICRP Publication 108 using an effective radius.

The conversion factors for depth-profiled ^{134}Cs and ^{137}Cs characterized by the relaxation depth were also estimated. The conversion factors are expressed by the factor for a uniform distribution at the 0–0.5 cm surface multiplied by a soil self-shielding factor of 0.74 for ^{134}Cs and 0.71 for ^{137}Cs and with a relaxation depth of 1.3 g/cm^2.

The external, the internal and the total exposures for 13 sampled macaques were estimated using the calculated conversion factors. The estimated cumulative exposures for the periods from the accident occurred to the sampling date, ranged from 0.26 to 1.6 Gy. The average exposure was 0.64 Gy in averaged over the 11 sampled macaques except for the 2 macaques which might be born after the FNPP accident.

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