External and internal radiation doses from the Fukushima Daiichi Nuclear Power Plant accident received by residents of Chiba, Japan

Hikaru AMANO*, Yuji OHTA, Shigeru BANBA, Takeshi MAEYAMA, Yoshihiro IKEUCHI, and Takao MORIMOTO

Japan Chemical Analysis Center, 295-3 Sanno-cho, Inage-ku, Chiba-shi, Chiba 263-0002, Japan
*h-amano@jcac.or.jp

Radioactive substances discharged into the atmosphere from the damaged Fukushima Daiichi Nuclear Power Plant (NPP) first reached the Chiba-City on March 15, 2011. Atmospheric and tap water samples were collected from March 2011 to August 2012 to measure of radioactivity in the Chiba-City, about 220 km SSE of the Fukushima NPP. We then used the data to analyze the external and internal (from inhalation of contaminated air or ingestion of contaminated drinking water) radiation doses received by the residents of the Chiba-City after the accident.

Keywords: *Fukushima NPP accident, Chiba-City, External radiation, Atmosphere, Tap water, Dose estimation*

1. Introduction

Large amounts of radioactive substances were released into the environment from the damaged Fukushima Daiichi Nuclear Power Plant (NPP). Those atmosphere discharges first reached the Chiba-City on March 15, 2011. Atmospheric and fallout deposition samples were collected beginning on March 14, 2011 and tap water samples were collected beginning on March 19, 2011 by the Japan Chemical Analysis Center (JCAC) in the Chiba-City, about 220 km SSE of the Fukushima NPP and adjacent to downtown Tokyo, which is 216 km SSE of the NPP.

We measured the radioactivity of samples collected over a period of more than 1 y after the accident (through August 2012), and analyzed both external radiation doses and internal doses from inhalation of contaminated air and ingestion of contaminated drinking water by the residents of the Chiba-City. The population of the Chiba-City in March 2011 was 962,436.

2. Experimental

Airborne particles and gaseous chemical species were sampled at 1.5 m above ground level at the JCAC. Airborne particles and gaseous iodine were collected continuously by a cellulose-glass-fiber filter (Toyo HE-40T) in combination with an activated charcoal cartridge containing 10% triethylenediamine (Toyo CHC-50). The filter and cartridge were exchanged every day until June 17, 2011, and once a week thereafter with a different filter-cartridge combination (HE-40T + ADVANTEC CP-20). Air was sampled with a low-volume air sampler; the air flow rate was regulated at around 90 L/min.

Tap water was collected from a faucet in a laboratory at JCAC in a 2-L Marinelli beaker daily for the first 3 months and weekly thereafter.

Radioactivity of the samples was measured directly by gamma-ray spectrometry with a Ge detector. A coincidence-summing correction was applied to the ^{134}Cs activity [1]. The counting efficiency of the Ge detector was calibrated by using agar standard samples of the same shape and volume prepared from standard sources. Directly after the accident, the counting times were usually 3600 s or longer. For a counting time of 3600 s, the detection limits were 1.4×10^{-3} Bq m^{-3} (daily sampling) and 1.9×10^{-4} Bq m^{-3} (weekly sampling) for atmospheric ^{137}Cs, and 3.8×10^{-1} Bq L^{-1} for ^{137}Cs in tap water.

Total external gamma-radiation doses were continuously monitored at the JCAC with a NaI (Tl) scintillation detector at 1.5 m above ground level at the center of a 10 × 10 m lawn.

The external radiation doses and the internal radiation doses from inhalation or from ingestion of tap water were estimated for residents of the Chiba-City following the accident.

3. Results and discussion

Almost all measured data at the JCAC are available on the web[2] and in the literature [1),3)].

Total external gamma-radiation levels peaked three times (on 15, 16, and 21 March), and the maximum dose rate was 0.5 μGy h^{-1}. The peaks on 15 and 16 March were mainly due to ^{133}Xe, ^{131}I, and ^{132}I, and the peak on 21 March was due mainly to ^{131}I, ^{132}I, ^{134}Cs, and ^{137}Cs delivered to the ground by rainfall [3)].

External exposure caused by the accident (i.e., above the background level) was estimated to be 69 μSv in March, 99 μSv in April, and 84 μSv in May 2011(Table 1). An exposure of 25.5 nSv h^{-1} from natural background radiation was estimated by averaging the measurements of the previous 1-y period (March 2010 to February 2011, Figure 1). These doses were calculated for someone who remained outside on the JCAC lawn for an entire day.

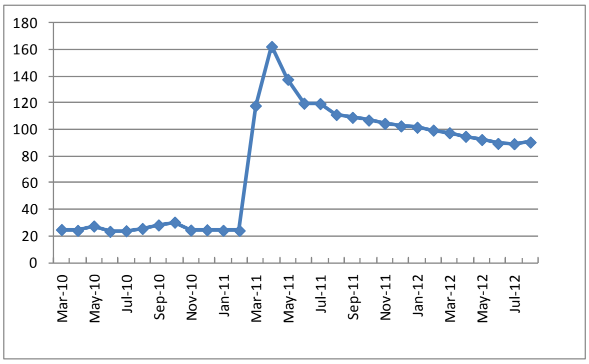

Fig. 1 Monthly averaged total external dose rate (nGy h^{-1}) at JCAC in Chiba-City.

The measurement unit, gray (Gy), is the SI equivalent of the air kerma. In this report, 1 Sv is considered equivalent to 1 Gy. At the end of the study period (August 2012), the radiation level was around 90.5 nGy h^{-1}(Figure 1). This radiation level is not expected to decline rapidly, because surface contamination is mainly caused by ^{134}Cs (half-life, 2 y) and ^{137}Cs (half-life, 30 y).

During the first three months after the NPP accident, the maximum daily concentrations of airborne radionuclides observed at the JCAC were 4.7×10^{1} Bq m^{-3} of ^{131}I, 7.5 Bq m^{-3} of ^{137}Cs, and 6.1 Bq m^{-3} of ^{134}Cs, and 6.6 Bq m^{-3} of ^{132}Te[1)].

Age-dependent internal doses were estimated for ^{131}I, ^{137}Cs, ^{134}Cs, and ^{132}Te, because of their longer half-lives and their considerable atmospheric concentrations directly after the accident.

The internal doses from inhalation of airborne materials were estimated from the measured atmospheric radionuclide concentrations by using the International Commission on Radiological Protection (ICRP) dose coefficients [4)] for three-month-old infants (<1 y of age), five-year-old children (2 to 7 y), and adults (>17 y) (Table 1) and by considering a daily breathing rate of

Table 1 Radiation doses (μSv) in the Chiba-City after the Fukushima NPP accident.

Month-Year	External	Internal																							
		Inhalation												Ingestion											
		Adult				5-y-old child				3-month-old infant				Adult				5-y-old child				3-month-old infant			
		^{134}Cs	^{137}Cs	^{131}I	^{132}Te	^{134}Cs	^{137}Cs	^{131}I	^{132}Te	^{134}Cs	^{137}Cs	^{131}I	^{132}Te	^{134}Cs	^{137}Cs	^{131}I	^{132}Te	^{134}Cs	^{137}Cs	^{131}I	^{132}Te	^{134}Cs	^{137}Cs	^{131}I	^{132}Te
Mar-11	68.8	4.06	9.61	49.7	0.75	3.27	6.78	96.3	1.39	1.83	3.49	55.5	1.18	0.39	0.29	8.18	0.002	0.16	0.13	22.5	0.004	0.23	0.009	79.3	0.211
Apr-11	98.5	0.13	2.94	0.86	3E-04	0.11	0.21	1.66	6E-04	0.006	0.11	0.96	5E-04	0.47	0.3	7.29	0	0.2	0.13	20.1	0	0.28	0.009	70.7	0
May-11	83.5	0.03	0.06	0.02	0	0.002	0.004	0.004	0	0.001	0.002	0.002	0	0.41	0.26	0.42	0	0.17	0.12	1.1	0	0.24	0.008	4.03	0
Jun-11	67.8	0.02	0.04	0	0	0.002	0.003	0	0	0.0009	0.001	0	0	0.4	0.25	0	0	0.16	0.11	0	0	0.23	0.008	0	0
Jul-11	69.9	0..005	0.0008	0	0	0.0004	0.0005	0	0	0.0002	0.0003	0	0	0.41	0.25	0	0	0.17	0.11	0	0	0.24	0.008	0	0
Aug-11	63.8	0.005	0.0004	0	0	0.0004	0.0003	0	0	0.0002	0.0001	0	0	0.41	0.25	0	0	0.17	0.11	0	0	0.24	0.008	0	0
Sep-11	60.2	0.007	0.0006	0	0	0.0006	0.0004	0	0	0.0003	0.0002	0	0	0.4	0.25	0	0	0.17	0.11	0	0	0.23	0.008	0	0
Oct-11	60.7	0.005	0.0005	0	0	0.0004	0.0003	0	0	0.0002	0.0002	0	0	0.41	0.25	0	0	0.17	0.11	0	0	0.24	0.008	0	0
Nov-11	57	0.005	0.0004	0	0	0.0004	0.0003	0	0	0.0002	0.0002	0	0	0.4	0.25	0	0	0.16	0.11	0	0	0.23	0.008	0	0
Dec-11	57.4	0.006	0.0006	0	0	0.0005	0.0004	0	0	0.0003	0.0002	0	0	0.41	0.25	0	0	0.17	0.11	0	0	0.24	0.008	0	0
Jan-12	56.7	0.005	0.0007	0	0	0.0004	0.0005	0	0	0.0002	0.0002	0	0	0.41	0.25	0	0	0.17	0.11	0	0	0.24	0.008	0	0
Feb-12	51.5	0.005	0.0004	0	0	0.0004	0.0003	0	0	0.0002	0.0002	0	0	0.38	0.24	0	0	0.16	0.11	0	0	0.23	0.007	0	0
Mar-12	53.6	0.007	0.0006	0	0	0.0006	0.0004	0	0	0.0003	0.0002	0	0	0.41	0.25	0	0	0.17	0.11	0	0	0.24	0.008	0	0
Apr-12	50	0.005	0.0004	0	0	0.0004	0.0003	0	0	0.0002	0.0002	0	0	0.4	0.25	0	0	0.16	0.11	0	0	0.23	0.008	0	0
May-12	49.8	0.007	0.0006	0	0	0.0006	0.0004	0	0	0.0003	0.0002	0	0	0.41	0.25	0	0	0.17	0.11	0	0	0.24	0.008	0	0
Jun-12	46.1	0.006	0.0005	0	0	0.0005	0.0004	0	0	0.0003	0.0002	0	0	0.4	0.25	0	0	0.16	0.11	0	0	0.23	0.008	0	0
Jul-12	47.5	0.005	0.0005	0	0	0.0004	0.0003	0	0	0.0002	0.0002	0	0	0.41	0.25	0	0	0.17	0.11	0	0	0.24	0.008	0	0
Aug-12	48.4	0.007	0.0006	0	0	0.0006	0.0004	0	0	0.0003	0.0002	0	0	0.41	0.25	0	0	0.17	0.11	0	0	0.24	0.008	0	0

2.86 m^3 for infants, 8.72 m^3 for children, and 22.2 m^3 for adults [5)]. Inhalation doses of ^{134}Cs and ^{137}Cs were calculated using the detection limit concentration if the measured value was less than the detection limit. These doses were calculated conservatively for people standing outside all day inhaling ambient air.

The total committed effective doses from inhalation of the four radionuclides in March, April, and May 2011 were respectively 64.1, 3.9, and 0.1 µSv for adults; 108, 2.0, and 0.1 µSv for five-year-old children; and 62.0, 11.2, and 0.1 µSv for three-month-old infants (Table 1). The committed effective dose from inhalation of the four radionuclides was dominated by ^{131}I in the first month, but in the second month, the doses from ^{134}Cs and ^{137}Cs were only slightly lower than that from ^{131}I. In March 2011, the inhalation dose was highest in one-year-old children (1 to 2 y, 111 µ Sv) closely followed by the dose in five-year-old children (108 µ Sv).

The committed effective doses from ingestion of tap water in infants, children, and adults were estimated from the radionuclide concentrations measured in tap water by using the ICRP dose coefficients [4)] and by assuming daily ingestion of 0.71 L by infants, 1.0 L by children, and 1.65 L by adults [6)]. The total committed effective doses from ingestion of the four radionuclides in March, April, and May 2011 were respectively 8.9, 8.1, and 1.1 µSv for adults; 22.8, 20.4, and 1.4 µSv for five-year-old children; and 79.8, 71.0, and 4.3 µSv for three-month-old infants (Table 1). The drinking water ingestion dose was dominated by ^{131}I in all age groups during March, April, and May 2011. The ingestion dose was highest in three-month-old infants, followed by five-year-old children and adults, among these three groups.

The highest committed effective doses between March 2011 and August 2012 for residents of the Chiba-City were from external radiation, but directly after the accident internal radiation doses exceeded external radiation doses (Figure 2). The committed effective doses during March 2011 to February 2012 due to the accident were 890 µSv (external, 800; inhalation, 66; ingestion, 24 µSv) for adults, 950 µSv (800, 110, and 47 µSv) for five-year-old children, and 1020 µSv (800, 63, and 160 µSv) for three-month-old infants, where internal radiation was from inhalation of contaminated air and ingestion of contaminated drinking water.

These estimates were obtained from the JCAC measurements by making several assumptions. The internal dose from ingestion of contaminated foods was not estimated, although it might be an important quantity. The amount of foods consumed by individuals varies widely, depending on the locality, food availability, and cultural dietary preferences. Therefore, estimation of the internal dose from consumption of contaminated food is left for future studies.

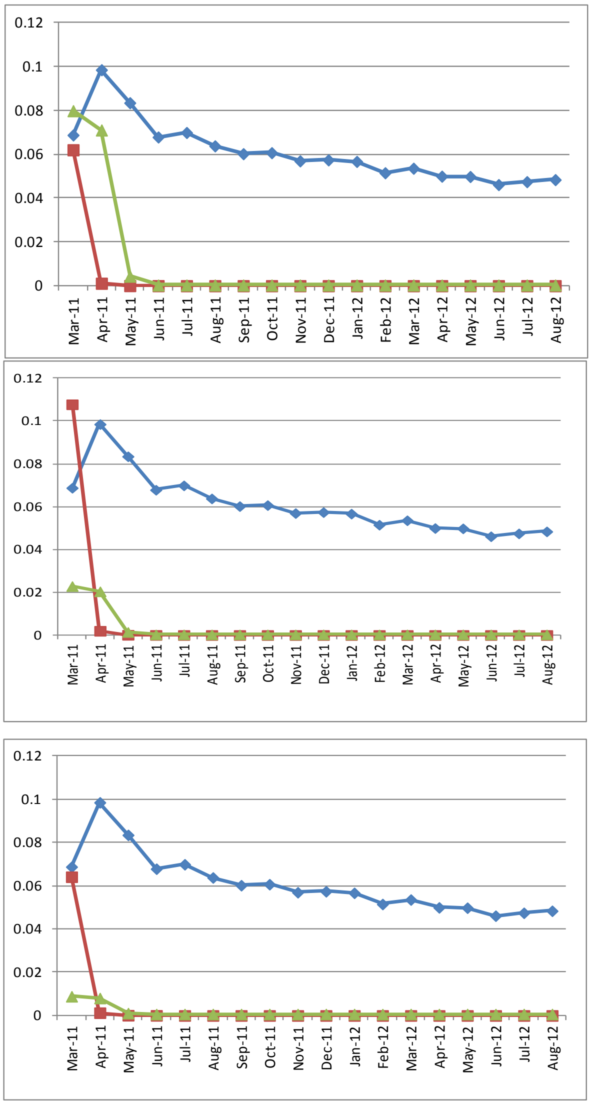

Fig. 2 Age-dependent committed effective doses (mSv); ◆ External exposure, ■ Internal exposure (Inhalation), ▲ Internal exposure (Ingestion of tap water): top, three-month-old infants; middle, five-year-old children; bottom, adults (>17 y).

4. Conclusion

Atmospheric, fallout deposition, and tap water samples were collected at JCAC in the Chiba-City, about

220 km SSE of the Fukushima NPP. For comparison, downtown Tokyo is about 216 km SSE of the Fukushima NPP. Though downtown Tokyo and the Chiba-City are nearby, radiation doses received by the Tokyo metropolitan residents should be estimated separately, because the contamination level is different. External and internal (due to inhalation and ingestion of tap water) radiation doses received by residents of the Chiba-City from the Fukushima NPP accident during a period of more than 1 y following the accident were estimated.

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