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Somatic mutation frequencies in the stamen hairs of *Tradescantia* grown in soil samples from the Bikini Island

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ABSTRACT

Somatic pink mutation frequencies in the stamen hairs of *Tradescantia* BNL 02 clone grown for 76 days in two soil samples taken from the Bikini Island (where a hydrogen bomb explosion test had been conducted in 1954) were investigated. A significantly high mutation frequency (2.58 ± 0.17 pink mutant events per 10^3 hairs or 1.34 ± 0.09 pink mutant events per 10^4 hair-cell divisions) was observed for the plant grown in one of the two Bikini soil samples, as compared to the control plants (1.70 ± 0.14 or 0.88 ± 0.07, respectively) grown in the field soil of Saitama University. The soil sample which caused the significant increase in mutation frequency contained $6{,}880 \pm 330$ mBq/g ^{137}Cs, 62.5 ± 4.4 mBq/g ^{60}Co, and some other nuclides; a 150 μR/hr exposure rate being measured on the surface of the soil sample. The effective cumulative external exposures measured for the inflorescences of the plant grown in this soil sample averaged at most 60.8 mR, being too small to explain the significant elevation in mutation frequency observed. On the other hand, internal exposure due to uptake of radioactive nuclides was estimated to be 125 mrad (1.25 mGy) as an accumulated effective dose, mainly based on a gamma-spectrometrical analysis. However, it seemed highly likely that this value of internal exposure was a considerable underestimate, and the internal exposure was considered to be more significant than the external exposure.

1. INTRODUCTION

Nuclear explosions have been repeated a great number of times since 1945 in air, water, and underground, scattering into the global environment a large quantity of man-made radioactive nuclides, many of which have not previously existed on the Earth. Commercial uses of nuclear energy have been promoted on a large scale in the last three decades, producing also a huge amount of man-made radioactive nuclides; a part of them has been accidentally released to the environment (as serious reactor accidents occurred at Chernobyl in 1986 and at Three Mile Island in 1979) or being discharged daily (some other parts may be released eventually). Uses of radioisotopes in various ways and forms have also expanded.

One of the deepest concerns in recent years about such various man-made

radioactive nuclides is that some of them are concentrated greatly in biological tissues (Ichikawa, 1981a, 1981b, 1991). For example, radioactive iodine, just as non-radioactive natural iodine, is known to be concentrated from air into plant tissues with an extremely high concentration factor of $2.0–10\times10^6$ (Marter, 1963; Soldat, 1963). Such a high concentration is never observed with natural radioactive nuclides which have been present on the Earth throughout the long evolutionary courses of living organisms, but is specifically conspicuous with man-made ratioactive nuclides (of the elements possessing no radioactive nuclides naturally) which no organisms have ever encountered (Ichikawa, 1981b). It is therefore considered that, in the case of man-made radioactive nuclides, internal exposure must be more significant than external exposure (Ichikawa, 1981b).

The present study was conducted to investigate the genetic effects of man-made radioactive nuclides residing in the environment at low levels. By cultivating *Tradescantia* tester plants heterozygous for flower color in soil samples collected from the Bikini Island where a hydrogen bomb explosion test had been conducted in 1954, somatic mutation frequency in the stamen hairs was examined. The *Tradescantia* stamen-hair system has proven to be one of the most suitable materials to study the genetic effects of low-level radiations (Nayar et al., 1970; Ichikawa, 1971, 1981b, 1990; Sparrow et al., 1972; Underbrink et al., 1973; Ichikawa and Takahashi, 1977; Ichikawa et al., 1981) or radioactivity (Nayar et al., 1970; Nauman et al., 1979; Tano and Yamaguchi, 1979; Bingo et al., 1981; Ichikawa, 1981a; Schairer and Sautkulis, 1982; Tano et al., 1984). A part of the results obtained in the present study has been briefly reported (Ichikawa and Nagashima, 1979) or referred (Ichikawa, 1981b, 1991).

2. MATERIALS AND METHODS

The tester plant material used was BNL 02 clone of *Tradescantia*, a diploid hybrid clone ($2n=12$) heterozygous for flower color (blue/pink; the blue color being dominant). This clone has been frequently used in studies of somatic mutations (Ichikawa et al., 1969, 1978, 1990; Nayar et al., 1970; Sparrow et al., 1972; Underbrink et al., 1973; Sparrow and Sparrow, 1976; Ichikawa and Takahashi, 1978; Nauman et al., 1979; Tano and Yamaguchi, 1979; Tano et al., 1984; Ichikawa, 1984, 1991), and its genetic nature has been also studied (Mericle and Mericle, 1967, 1971, 1973; Christianson, 1975; Ichikawa, 1991).

Obtaining a special permission of the Minister of Agriculture, Forestry and Fishery (issued to the senior author dated June 12, 1978), two soil samples were collected by the staff of a special program producing team of the Nippon Television Network Corp. (NTV) from the Bikini Island. The radiation levels measured with a Geiger counter (Aloka's TGS-111) at the location of collecting the soil samples were 133 and 158 μR/hr at about 50 cm above and 10 cm below the ground level (GL), respectively. The soil samples were taken back to Japan on

July 31, 1978, and, after examination at the Narita Branch of the Yokohama Plant Quarantine Office, the soil samples were received by the authors on August 9.

One of the two soil samples was taken from about 10–20 cm in depth (B_1 hereafter) and weighed 1.6 kg; the other was the surface soild (B_2 hereafter) weighing 1.4 kg. A part (200 g) of the B_1 soil sample was used for gamma-spectrometrical analysis conducted at the National Institute of Radiological Sciences, Chiba, with a Ge(Li) semi-conductor detector and a multi-channel (4,096 ch.) pulse height analyzer, in order to detect radioactive nuclides contained. A similar analysis could not be done on the B_2 soil sample, because the entire 1.4 kg amount was necessary for cultivating one plant.

Five plants of BNL 02 clone, each possessing several young inflorescences of flowering size, were prepared and were potted on September 2 in five 18 cm clay pots, two of which were filled with the two Bikini soil samples, B_1 and B_2, respetively, and the remaining three filled with field soil of Saitama University (U_1-U_3 hereafter). The potted plants were grown in a sun-beamed growth chamber (Koitotron 3S-135) in which the temperature was maintained at 25 ± 2°C during the day and 20 ± 1°C at night and the day length was kept to be 16 hr. In the Koitotron, the two pots with the B_1 and B_2 soil samples were placed being separated from the three pots with the field soil as shown in Fig. 1. Each pot was put in a 3 cm deep 28×22 cm plastic tray for recovering any flushed soil. On

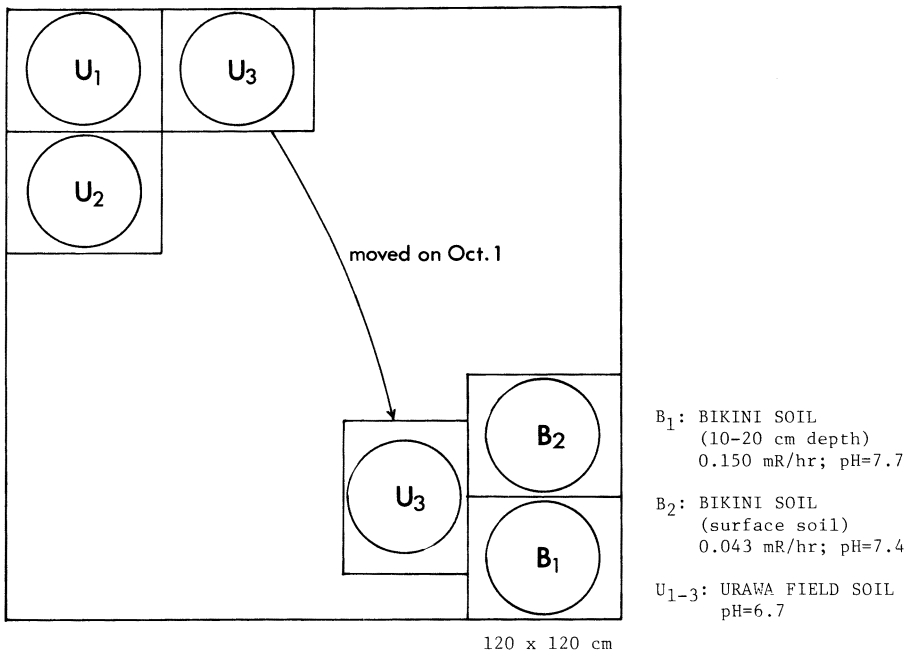

Fig. 1. Positions in the growth chamber of the two plants grown in the B_1 and B_2 soil samples from the Bikini Island and the three plants grown in the field soil of Saitama University, Urawa.

October 1, one of the control plants with the filed soil (U_3) was moved to the position adjacent to the pots with the B_1 and B_2 soil samples (see Fig. 1), in order to examine the effect of external exposure alone.

Scoring pink mutation frequency in the stamen hairs of these plants was performed daily from September 3 through November 17. For scoring mutations, all the flowers that opened during the scoring period were collected daily from each plant used. The number of stamen hairs was counted on each stamen (each flower has three antipetalous and three antisepalous stamens), and the number of hair cells was also counted on ten representative hairs (distal three, middle four and basal three hairs) each of one antipetalous and one antisepalous stamens per flower as described earlier (Ichikawa and Takahashi, 1977, 1978). A single pink cell or two or more contiguous pink cells in a hair was regarded as one pink mutant event, following earlier definition (Ichikawa and Sparrow, 1968; Ichikawa et al., 1969). The number of pink mutant events per 10^3 hairs was calculated, and the number of pink mutant events per 10^4 hair-cell divisions was also obtained by dividing the mutation frequency per hair by one less than the average number of cells per hair (Sparrow and Sparrow, 1976; Ichikawa and Takahashi, 1977, 1978).

During the experimental period, exposure rate at 30 cm above the soil surface of each pot was measured three times (on September 2, October 1 and November 1) with a Geiger counter (Aloka's TGS-111), in order to calculate average external exposure of inflorescences of each plant. The counter was calibrated before use with a ^{60}Co source at the Radioisotope Laboratory, Saitama University.

After the scoring period, the inflorescences (mostly old being composed of small numbers of remaining flower buds at the end of scoring) with bracts and 6–10 cm long stems were harvested from the two plants grown in the B_1 and B_2 soil samples separately (67.4 and 62.2 g, respectively), and were used for gamma-spectrometrical analysis at the Radioisotope Center, University of Tokyo, to know the concentrations of radioactive nuclides taken up.

3. RESULTS

At the time of receiving the B_1 and B_2 soil samples, exposure rates of 150 and 43 μR/hr were measured on their surfaces, respectively. The gamma-spectrometrical analysis of the B_1 soil sample revealed that it contained $6{,}880 \pm 330$ mBq/g ^{137}Cs, 62.5 ± 4.4 mBq/g ^{60}Co, and traces of ^{155}Eu and ^{241}Am.

The pH values of the B_1 and B_2 soil samples were measured to be 7.7 and 7.4, respectively, while the pH value of the field soil (U_1-U_3) of Saitama University was 6.7. All the five plants used grew well with these soil samples or with the field soil.

Average accumulated external exposures calculated for the inflorescences of the five plants (based on the exposure rates measured three times for each plant) are

Table 1. Average accumulated external exposures of the inflorescence of the five plants of *Tradescantia* BNL 02 clone grown in soil samples from the Bikini Island (B_1, B_2) or in the field soil of Saitama University (U_1-U_3)

Pot	Measured on	Exposure rate (μR/hr)[a]	Period	Days	Accumulated external exposure (mR)[b] on
B_1	Sep 2	120			78.4 Sep 30
	Oct 1	113	Sep 2 to Nov 17	76	162.4 Oct 31
	Nov 1	113			208.5 Nov 17
B_2	Sep 2	95			63.2 Sep 30
	Oct 1	93	Sep 2 to Nov 17	76	131.3 Oct 31
	Nov 1	90			168.0 Nov 17
U_1	Sep 2	10			6.7 Sep 30
	Oct 1	10	Sep 2 to Nov 17	76	13.8 Oct 31
	Nov 1	9			17.5 Nov 17
U_2	Sep 2	12			7.7 Sep 30
	Oct 1	11	Sep 2 to Nov 17	76	16.3 Oct 31
	Nov 1	12			21.2 Nov 17
U_3	Sep 2	14	Sep 2 to Oct 1	29	9.4 Sep 30
	Oct 1	67	Oct 1 to Nov 17	47	59.6 Oct 31
	Nov 1	68			87.4 Nov 17

[a] Measured at 30 cm above the soil surface.

[b] Not the effective external exposure of stamen hairs (see Table 2 for effective exposures).

Table 2. Average effective external exposures of the stamen hairs of the five plants of *Tradescantia* BNL 02 clone grown in soil samples from the Bikini Island (B_1, B_2) or in the field soil of Saitama University (U_1-U_3)

Stamen hairs observed on	Effective external exposure (mR)[a]				
	B_1	B_2	U_1	U_2	U_3
Sep 8	0	0	0	0	0
Sep 15	22.9	18.2	1.9	2.3	2.7
Sep 22	37.8	30.2	3.2	3.8	4.5
Sep 29	40.4	32.6	3.5	4.0	4.9
Oct 6	43.0	35.0	3.7	4.2	5.2
Oct 13	45.7	37.3	4.0	4.5	14.5
Oct 20	48.7	39.6	4.2	4.8	22.8
Oct 27	51.7	41.9	4.4	5.2	24.7
Nov 3	54.8	44.2	4.6	5.6	26.5
Nov 10	57.8	46.4	4.8	5.9	28.4
Nov 17	60.8	48.8	5.0	6.3	30.3

[a] Calculated based on the assumption that the exposure delivered 7–19 days before flowering was effective and the exposure delivered earlier had a 16% effectiveness. The assumption was made based on the raw data of earlier publications (Ichikawa et al., 1969, 1978).

presented in Table 1. Based on these data, average effective external exposures of the stamen hairs of these five plants could also be calculated as shown in Table 2, using the following equation:

$$D_e=\sum [T_e+0.16(T-T_e-6)]R, \quad (1)$$

where, D_e is effective exposure in mR, R is exposure rate in mR/day (calculated based on the three-time measurements), T_e is the major 13-day period effective for induction of mutation (7 to 19 days before flowering), and T is the total number of days being exposed (see the footnote to Table 2 for two constants). The effective external exposures increased relatively rapidly in the early scoring periods but the increase diminished in later scoring periods. The effective cumulative exposure was at most 60.8 mR, which was calculated for the plant grown in the B_1 soil sample.

The data collected from the stamen hairs of the five plants used are summarized in Table 3. In total, 283,531 stamen hairs or about 5,742,000 stamen-hair cells were observed, and 595 pink mutant events were detected. The data from each of the B_1 and B_2 plants (the plants grown in the B_1 and B_2 soil samples, respectively) are grouped into five two-week periods in the table, excepting those for the first six days when no radiation effect was expected to be observed (Ichikawa et al., 1969, 1978). As for the U_1, U_2 and U_3 plants (the plants grown in the field soil of Saitama University), on the other hand, the data from the three plants are pooled until October 6 (sixth day after changing the position of the U_3 plant; see Fig. 1), but the pooled data from the U_1 and U_2 plants and the data from the U_3 plant are separately shown in the table after October 7, each grouping into every-two-week periods.

Significantly higher somatic mutation frequencies than those in the control plants (the U_1, U_2 and U_3 plants until October 6, and the U_1 and U_2 plants after October 7) were obtained from the B_1 plant. Namely, as shown in Table 3, the mutation frequencies of the B_1 plant for two periods of two weeks (September 9 to 22 and November 4 to 17) were significantly higher than the corresponding frequencies in the control plants, and the mutation frequencies pooled for whole scoring period, four weeks of September 9 through October 6, six weeks of October 7 through November 17, and ten weeks of September 9 through November 17 were all highly significantly different from the corresponding control frequencies.

The mutation frequencies obtained from the B_2 plant were also generally higher than those in the control plants (Table 3), but no statistical differences were found between them. The mutation frequencies obtained from the U_3 plant after moving it to the position adjacent to the B_1 and B_2 plants were also higher than those in the control plants in the last two periods of two weeks (Table 3), but they were not different significantly from the corresponding control frequencies.

The gamma-spectrometrical analysis on the inflorescences (mostly old ones with

Table 3. Somatic pink mutation frequencies in the stamen hairs of the five plants of *Tradescantia* BNL 02 clone grown in soil samples from the Bikini Island (B_1, B_2) or in the field soil of Saitama University (U_1-U_3)

Grown in	Scoring period	No. of hairs observed	No. of pink mutant events	No. of pink mutant events /10^3 hairs (±SE)	Average no. of cells /hair	No. of pink mutant events/10^4 cell divisions (±SE)
B_1	Sep 3–8	1,632	3	1.84±1.06	22.54	0.85±0.49
	Sep 3–22	10,492	27	2.57±0.49*	19.80	1.37±0.26*
	Sep 23–Oct 6	12,802	31	2.42±0.43	19.82	1.29±0.23
	Oct 7–20	15,919	41	2.58±0.40	20.74	1.30±0.20
	Oct 21–Nov 3	23,023	54	2.35±0.32	20.57	1.20±0.16
	Nov 4–17	23,820	69	2.90±0.35*	20.18	1.51±0.18*
	Total	87,688	225	2.57±0.17***	20.33	1.33±0.09***
	Sep 9–Oct 6	23,294	58	2.49±0.33**	19.81	1.32±0.17***
	Oct 7–Nov 17	62,762	164	2.61±0.20***	20.47	1.34±0.10***
	Sep 9–Nov 17	86,056	222	2.58±0.17***	20.29	1.34±0.09***
B_2	Sep 3–8	1,733	4	2.28±1.14	22.87	1.04±0.52
	Sep 9–22	13,877	30	2.16±0.39	19.98	1.14±0.21
	Sep 23–Oct 6	12,730	21	1.65±0.36	19.49	0.89±0.19
	Oct 7–20	13,908	24	1.73±0.35	20.08	0.90±0.18
	Oct 21–Nov 3	20,082	45	2.24±0.33	20.15	1.17±0.17
	Nov 4–17	18,812	39	2.07±0.33	19.86	1.10±0.18
	Total	81,162	163	2.01±0.16	20.00	1.06±0.08
	Sep 9–Oct 6	26,607	51	1.92±0.27	19.75	1.02±0.14
	Oct 7–Nov 17	52,802	108	2.05±0.20	20.03	1.07±0.10
	Sep 9–Nov 17	79,409	159	2.00±0.16	19.93	1.06±0.08
U_1-U_3	Sep 3–8	5,729	13	2.27±0.63	22.19	1.07±0.30
	Sep 9–22	23,934	37	1.55±0.25	20.45	0.79±0.13
	Sep 23–Oct 6	21,543	36	1.67±0.28	20.17	0.87±0.15
U_1, U_2	Oct 7–20	14,455	28	1.94±0.37	20.81	0.98±0.18
	Oct 21–Nov 3	14,339	24	1.67±0.34	20.03	0.88±0.18
	Nov 4–17	15,164	27	1.78±0.34	19.74	0.95±0.18
	Total	95,164	165	1.73±0.13	20.37	0.90±0.07
	Sep 9–Oct 6	45,477	73	1.61±0.19	20.32	0.83±0.10
	Oct 7–Nov 17	43,958	79	1.80±0.20	20.18	0.94±0.11
	Sep 9–Nov 17	89,435	152	1.70±0.14	20.25	0.88±0.07
U_3	Oct 7–20	5,687	10	1.76±0.56	20.56	0.90±0.28
	Oct 21–Nov 3	5,163	13	2.52±0.70	20.29	1.31±0.36
	Nov 4–17	8,667	19	2.19±0.50	20.21	1.14±0.26
	Oct 7–Nov 17	19,517	42	2.15±0.33	20.34	1.11±0.17

* Significant at 5% level. ** Significant at 2% level. *** Significant at 1% level.

Table 4. Concentrations of radioactive nuclides detected from the B_1 soil and fruit samples collected from the Bikini Island and from *Tradescantia* grown in the Bikini soil samples, and the radiation levels measured at the places of collection

Material (g)	Radioactivity in mBq/g				Exposure rate (μR/hr) at 10 cm below GL
	^{137}Cs	^{90}Sr	^{60}Co	Others	
Soil (B_1) (200)	6,880±330	N.A.[a]	62.5±4.4	[b]	158
Coconut fruits[c] (378–1,055)	7,030–8,880	N.A.	—	—	53–70
Pandanus fruit (213)	4,440	740	—	—	34
Breadfruit (300)	1,670	150	—	—	22
Tradescantia[d] (67.4+62.2)	7,770±410	N.A.	24.5±2.2	—	—

[a] Not analyzed.
[b] Traces of ^{155}Eu and ^{241}Am.
[c] Four fruits.
[d] Samples from the B_1 and B_2 plants (67.4 and 62.2 g, respectively) were put together (see text).

only a few remaining flower buds) with bracts and stems harvested after the scoring period was conducted putting the samples from the B_1 and B_2 plants together, because each of them alone was not enough in amount. The analysis revealed that the samples put together contained 7,770±410 mBq/g ^{137}Cs and 24.5±2.2 mBq/g ^{60}Co, as seen in Table 4.

4. DISCUSSION

Before conducting the present experiment with the Bikini soil samples, an experiment to grow the tester plants of BNL 02 clone in the Bikini Island was tried. Namely, 100 cuttings of the clone were prepared in Japan, carried to the Majuro Island (of the Marshall Islands) where nearly normal radioactivities were detected, and one half of them were then brought in the Bikini Island and grown there for 83 days (from April 4 through June 26, 1978). They were taken back to Japan for observation, together with those which had been left in the Majuro Island. However, the experiment was unsuccessful because of low surviving rates of the plants (only 11 in Bikini and 14 in Majuro survived) as well as very poor development of inflorescences, thus resulting in too small sample sizes (Ichikawa and Nagashima, 1979), probably due to the hot climate and the almost neutral day length in the Marshall Islands.

Significant increase of mutations: In the present experiment, on the other hand, highly significantly increased somatic pink mutation frequencies were observed in the stamen hairs of the plant grown in one (B_1) of the Bikini soil

samples (Table 3), which contained $6,880 \pm 330$ mBq/g ^{137}Cs, 62.5 ± 4.4 mBq/g ^{60}Co, and traces of ^{155}Eu and ^{241}Am (Table 4). The effective cumulative external exposure calculated for the young stamen hairs of the plant grown in this soil sample, based on the dosimetry conducted, reached at most 60.8 mR at the end of the scoring period (Table 2).

According to Sparrow et al. (1972), the doubling dose of pink mutations in the stamen hairs of BNL 02 clone after treating with 250-kVp X rays was only about 1 rad (10 mGy). The somatic pink mutation frequency of 1.64×10^{-3} pink mutant events per hair per R of ^{137}Cs gamma rays reported by Ichikawa et al. (1969) for BNL 02 clone also suggests that the doubling dose of pink mutation in this clone is only around 1 R. It has been repeatedly demonstrated that the dose-response curve of the somatic pink mutations in *Tradescantia* stamen hairs is linear in the range of smaller doses as well as at lower dose rates, as reviewed earlier (Ichikawa, 1981b, 1991).

It is therefore expected that the small external exposure of 60.8 mR could increase the mutation frequency only about 6% (by a factor of 1.06). However, the observed mutation frequencies of 2.58 ± 0.17 pink mutant events per 10^3 hairs and 1.34 ± 0.09 pink mutant events per 10^4 hair-cell divisions in the B_1 plant in the period of September 9 through November 17 are about 50% higher (about 1.5 times), compared to the corresponding control frequencies of 1.70 ± 0.14 pink mutant events per 10^3 hairs and 0.88 ± 0.07 pink mutant events per 10^4 hair-cell divisions (see Table 3). The results thus suggested that the mutation frequencies observed in the B_1 plant corresponded to those induced with about 500 mrad (5 mGy) or about 500 mR of X or gamma rays.

The mutation frequencies obtained from the B_2 plant and those from the U_3 plant (after moving it to the position adjacent to the B_1 and B_2 plants) appeared to be higher than the control frequencies, but no statistically significant differences were detected with the sample sizes observed (Table 3).

Significance of internal exposure: The above consideration suggests that the significantly increased somatic mutations in the B_1 plant might have been induced mainly by internal exposures from the radioactive nuclides (predominantly ^{137}Cs) taken up by the plant via roots and accumulated into the floral tissues.

Significance of internal exposures from the radioactive nuclides has been demonstrated experimentally using *Tradescantia* stamen hairs (Nayar et al., 1970; Nauman et al., 1979; Tano and Yamaguchi, 1979; Bingo et al., 1981; Ichikawa, 1981a; Schairer and Sautkulis, 1982; Tano et al., 1984) or reviewed (Ichikawa, 1981b, 1991). Especially, it has been reported that a small amount of ^{131}I which delivered only an extremely small beta-ray dose calculated to be between 0.3 and 1 rad (3 and 10 mGy) to stamen hairs could double the mutation frequency (Tano and Yamaguchi, 1979; Bingo et al., 1981).

In order to examine the extent of radioactive contamination of plant materials in the Bikini Island, four coconut fruits, one pandanus fruit and one breadfruit were

taken back to Japan together with the soil samples used, and they were analyzed gamma-spectrometrically at the National Institute of Radiological Sciences. Also, some parts of the pandanus fruit and the breadfruit were used for detecting ^{90}Sr chemically at the Meteorological Research Institute, Tsukuba. The results obtained are shown in Table 4. It is obvious that heavy contaminations of plants with ^{137}Cs and ^{90}Sr were occurring in the Bikini Island. It is also seen in Table 4 that there was a fairly high correlation between the ^{137}Cs concentrations in these fruits and the radiation levels measured at 10 cm below the ground level at the places where these fruits were collected.

A high concentration of ^{137}Cs and some ^{60}Co were also detected from the inflorescences (mostly old having only a few remaining flower buds) with bracts and stems of the B_1 and B_2 plants put together, which were taken after scoring mutations terminated (Table 4). The concentration of ^{137}Cs obtained from these samples put together was comparable to those from four coconut fruits and to that from the B_1 soil sample (see Table 4), indicating that the ^{137}Cs concentration in *Tradescantia* tissues reached a level comparable to or exceeding that in the soil used for the cultivation within the relatively short cultivation period of 76 days.

Calculations of internal exposures which might occur in the B_1 and B_2 plants were made using the following procedures. Firstly, since the gamma-spectrometrical analysis was conducted putting the samples from the B_1 and B_2 plants together, the concentrations of ^{137}Cs and ^{60}Co in each plant were calculated taking into consideration the exposure rates at the surfaces of the B_1 and B_2 soil samples (150 and 43 μR/hr, respectively), and the weights of the both plant samples before putting together (67.4 and 62.2 g, respectively). The resultant values obtained are shown in Table 5.

Table 5. Concentrations of ^{137}Cs and ^{60}Co in mBq/g calculated for the B_1 and B_2 plants grown in soil samples from the Bikini Island

Nuclide	B_1	B_2
^{137}Cs	11,800±600	3,390±180
^{60}Co	37.0±3.3	10.7±1.1

For calculating the internal beta-ray dose rates from ^{137}Cs, the following formula was used:

$$R_b = 1.38 \times 10^{-3} E_b C, \quad (2)$$

where, R_b is beta-ray dose rate in rad/day, E_b is average energy of beta rays in MeV, and C is concentration of nuclide in Bq/g. The E_b value for ^{137}Cs was cited from Kondo (1972) to be 0.227, although this nuclide emits 0.514 and 1.176 MeV_{max} beta rays in a ratio of 0.935:0.065. The decay of ^{137}Cs was ignored because this

Table 6. Internal dose rates calculated for the B_1 and B_2 plants grown in soil samples from the Bikini Island, and the effective internal doses at the end of scoring period

Source	Dose rate in mrad/day (μGy/day) for	
	B_1	B_2
^{137}Cs beta rays	3.70±0.19 (37.0±1.9)	1.06±0.06 (10.6±0.6)
^{60}Co beta rays	0.00476±0.00042 (0.0476±0.0042)	0.00138±0.00014 (0.0138±0.0014)
^{137}Cs gamma rays	0.122±0.006 (1.22±0.06)	0.0351±0.0019 (0.351±0.019)
Total[a]	3.83±0.19 (38.3±1.9)	1.10±0.06 (11.0±0.6)
	Effective internal dose in mrad (μGy)[a,b]	
	84.7±4.3 (847±43)	24.3±1.3 (243±13)

[a] Besides these dose rates or doses, 1.84±0.09 and 0.529±0.028 mrad (18.4±0.9 and 5.29±0.28 μGy)/day ^{90}Sr+^{90}Y beta-ray internal dose rates for the B_1 and B_2 plants, respectively, and 40.7±2.1 and 11.7±0.6 mrad (407±21 and 117±6 μGy) ^{90}Sr+^{90}Y beta-ray effective internal doses for the B_1 and B_2 plants, respectively, were estimated to have existed.

[b] See the footnote to Table 2.

nuclide has a long half-life of 30.1 years. The resultant dose rates obtained are shown in Table 6.

The internal beta-ray dose rates from ^{60}Co were calculated using the same formula and also ignoring the decay (a half-life of 5.27 years), but using E_b value of 0.093 (Kondo, 1972), and were found to be very low (Table 6).

It was necessary to consider the internal gamma-ray dose rates from ^{137}Cs. Since the energy of the 0.663 MeV gamma rays emitted from this nuclide is absorbed in biological tissues in a ratio of about 1% per 3 mm (Kondo, 1972), it was considered that 3.3% of the gamma-ray energy was absorbed in young stamen hairs in young flower buds which are located at relatively lower part of the inflorescence having a length, width and thickness of about 15, 10 and 7 mm, respectively, being covered with bracts. It was assumed here that the relative contribution of ^{137}Cs gamma rays was 3.3% of the beta rays from this nuclide, and the calculated values are shown in Table 6. The contribution of internal gamma rays from ^{60}Co was ignored here.

Adding these calculated dose rates, the B_1 and B_2 plants were calculated to have been exposed internally from ^{137}Cs and ^{60}Co at the total dose rates of 3.83±0.19 and 1.10±0.06 mrad (38.3±1.9 and 11.0±0.6 μGy)/day, respectively (Table 6). Based on these total dose rates, effective internal doses from these two nuclides at the end of the scoring period (see the footnote to Table 2) could be

calculated using the following equation which is a modified one of the equation (1):

$$D'_e=[T_e+0.16(T-T_e-6)]R_i\ , \tag{3}$$

where, D'_e is effective internal dose in mrad, and R_i is total internal dose rate in mrad/day. The resultant values were calculated to be 84.7 ± 4.3 and 24.3 ± 1.3 mrad (847 ± 43 and 243 ± 13 μGy) for the B_1 and B_2 plants, respectively, as seen in Table 6.

However, it was considered necessary to calculate the internal dose rates also for ^{90}Sr (which could not be detected gamma-spectrometrically since it emits only beta rays), because this nuclide was detected from pandanus fruit and breadfruit (see Table 4). From the data on these fruits, it was assumed that ^{90}Sr was present in the soil samples and taken up into plant tissues at a concentration of one tenth of ^{137}Cs. Using the above formula (2) and regarding the E_b to be 1.128 (Kondo, 1972; 0.198 for ^{90}Sr plus 0.93 for ^{90}Y which arises as the result of beta-decay of ^{90}Sr), beta-ray dose rates due to ^{90}Sr were calculated as shown in the footnote to Table 6. The decay of radioactivity of ^{90}Sr (a half-life of 28.0 years) was ignored here.

Adding the dose rates due to ^{90}Sr, the total internal dose rates for the B_1 and B_2 plants were calculated to be 5.67 ± 0.29 and 1.63 ± 0.09 mrad (56.7 ± 2.9 and 16.3 ± 0.9 μGy)/day, respectively. The total effective internal doses were thus 125 ± 6 and 36.0 ± 1.9 mrad (1.25 ± 0.06 and 0.360 ± 0.019 mGy) for the B_1 and B_2 plants, respectively.

Considering that the gamma-spectrometrical analysis was not conducted on young inflorescences alone but on the mass of inflorescences (mostly old; all the flowers that had opened had been removed for observation) plus bracts and stems, and that ^{137}Cs is usually selectively accumulated into actively growing tissues rather than into older tissues, the possibility of the above calculated values being underestimates is highly likely. Although it is difficult to figure out the extent of underestimation, the above calculations might have resulted in a nearly four-fold underestimation, since the increase in mutation frequency observed in the B_1 plant corresponded to that induced with about 500 mrad (5 mGy) of X or gamma rays. It is also likely, even if the calculations did not bring such a large underestimation, that the relative biological efficiency (RBE) values of internal beta rays from ^{137}Cs, ^{90}Sr and ^{90}Y were larger than 1, as demonstrated earlier for beta rays from ^{3}H (Nauman et al., 1979) and ^{131}I (Bingo et al., 1981).

The present demonstration of the significance of the internal exposures from ^{137}Cs and other radioactive nuclides further confirms similar conclusions on ^{3}H (Nauman et al., 1979; Schairer and Sautkulis, 1982; Tano et al., 1984), ^{131}I (Tano and Yamaguchi, 1979; Bingo et al., 1981; Ichikawa, 1981a), ^{232}Th (Nayar et al., 1970) and other nuclides (Nayer et al., 1970; Ichikawa, 1981a) reported earlier using *Tradescantia*.

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