Measuring individual external doses of Tokyo Electric Power Company Holdings employees living in Fukushima prefecture

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Abstract

Since the accident at Fukushima Daiichi Nuclear Power Plant, individual external doses of residents have been investigated. To accurately analyse survey data, a variety of information, including the activity patterns of many residents, needs to be integrated. However, such large-scale surveys have not yet been conducted and actual individual external doses in Fukushima are unclear. In this study, the individual external doses of approximately 300 Tokyo Electric Power Company Holdings employees, who live and work in Fukushima Prefecture outside the Fukushima Daiichi Nuclear Power Plant, were measured. The employees carried GPS loggers and personal dosimeters capable of measuring dose in counts per minute. The employees’ individual external doses were compared along with their activity patterns. It was found that the annual additional individual external dose estimated based upon actual measurements was 1 mSv or less, and the influence on the individual external dose was also revealed.

Keywords: individual external dose, individual external dose estimation, modeling and reduction factor, Fukushima nuclear accident

(Some figures may appear in colour only in the online journal)
1. Introduction

The 9.0-magnitude earthquake and tsunami on 11 March 2011 inflicted serious damage on the Fukushima Daiichi Nuclear Power Plant, and the accident released radioactive materials into the environment. Figure 1 shows air dose rates as reported based on airborne monitoring conducted during the first survey 9 years ago and the most recent survey. Decontamination and weathering over these nine years have reduced the air dose rate. Changes of the air dose rates have been reported by carborne survey as well as by airborne survey [1]. There is also the report on the change in the amount of deposition densities of radiocesium in the soil over time [2].

This paper presents the actual external exposure as reported based on individual external doses measured by Tokyo Electric Power Company Holdings employees living in Fukushima Prefecture.

An annual cumulative dose of 20 mSv estimated based upon the air dose rate has been set as the individual external dose value for rescission of evacuation orders issued after the accident at Fukushima Daiichi Nuclear Power Plant. An annual additional individual external dose of less than 1 mSv is the long-range target for the individual external dose that takes into account the ‘Practical Measures for Evacuees to Return Their Homes’ as recommended by the Nuclear Regulation Authority in November 2013 [4]. Both are based upon the presumption that an individual will be outside 8 h a day and inside a wooden building 16 h a day. However, because the individual external doses vary depending upon the outdoor air dose rate, type of building, air dose rate, activity pattern, and area of activity, an assessment needs to be conducted based upon actual measurements of individual doses. In order to estimate external exposure immediately after the accident when external exposure could not be measured, there is a report on the evaluation of external dose using various physical data and aircraft monitoring data without using actual measurements [5].

Some reports have evaluated the rate at which decontamination has reduced individual external dose and the annual individual external dose based upon measurements obtained from personal dosimeters (glass badges) [6–13]. Personal dosimeters for individuals have been distributed to each municipality and individual external doses have been ascertained ranging from several thousand residents to several tens of thousands. The glass badges have a personal dose lower measurement limit of 0.1 mSv and are well suited to assessing individual external dose over the long-term. However, they are not suited to analysing measurement results.

There is a method for measuring the connection between activity patterns and exposure dose where measurements are taken using a personal dosimeter (D-Shuttle), which is capable of recording the dose hourly over a period of approximately two weeks along with recording the individual’s activities [14, 15]. This is the method recommended by national and municipal verification committees. Naito et al combined D-Shuttle, global positioning system (GPS) logger records, and activity records describing the subjects’ activities over a measurement period ranging from 3 to 14 d. They analysed the individual doses of 87 residents of Fukushima city and other municipalities in the prefecture over the period from September 2013 until March 2015, and 38 residents of Iitate village over the period from September 2015 until May 2016 [16–18]. However, data in one-hour units is hardly sufficient for analysing the relation between individual external doses and their activities. Additionally, more data needs to be collected.

Accordingly, approximately 300 Tokyo Electric Power Company Holdings, Inc. (TEPCO) employees who reside and work mainly in Fukushima Prefecture carried personal dosimeters
Figure 1. Maps showing the air dose rate at 1 m above ground estimated based on the 1st airborne survey and the 13th airborne Survey [3]. Adapted from data in [3].

(a) 1st airborne survey (as of 29 April 2011)

(b) 13th airborne survey (as of 15 November 2018)
Table 1. Participants.

|                | Indoor Workers in Fukushima Prefecture | Outdoor Workers in Fukushima Prefecture | Workers in the Greater Tokyo Metropolitan Area | Total |
|----------------|-----------------------------------------|------------------------------------------|------------------------------------------------|-------|
| All participants (for periods of 1 to 6 d) | 127                                     | 150                                      | 16                                             | 293   |
| Participants classified according to conditions | 112                                     | 126                                      | 16                                             | 254   |
| Participants with activity records            | 36                                      | 27                                       | –                                              | 63    |

(DOSEe nano), capable of recording dose in one-minute units and GPS loggers. This data was analysed to estimate the annual additional individual external dose.

2. Materials and methods

2.1. Participants and measurement area

Individual external doses were measured of 277 employees residing and working in Fukushima Prefecture for Tokyo Electric Power Company Holdings, Inc. and 16 more employees working in the Greater Tokyo Metropolitan area for a maximum of six days, including non-workdays, over the period from November 2018 until March 2019. The participants were separated into indoor workers, who were primarily in offices, and outdoor workers, who were primarily engaged in fieldwork. Outdoor workers were mainly engaged in field management, dose surveys, and weeding work in contaminated areas and non-contaminated areas. Outdoor workers also included cases where the individuals were lodged near their workplace while working successively over several days. The employees’ duties included handling compensation for residents affected by the nuclear accident, cooperating with decontamination activities, promoting revitalisation, promoting sales of products and goods of Fukushima prefecture, and other work. The offices of the participants were located in Fukushima city, Koriyama city, Minamisoma city, Tomioka town, and Iwaki city. The participants resided near their offices. As shown in table 1, the total number of participants who took measurements for periods between one and six days is 293. 254 employees were able to measure their individual doses during their activities on workdays and non-workdays, and 63 people recorded their activities in addition to recording their locations with GPS logger data.

Using positional data and movement speeds of GPS loggers, locations where the participants remained for five minutes or longer and their movement paths were mapped using Google Maps JavaScript API on a map from the Geographical Survey Institute (figures 2 and 3) [19, 20]. The locations where participants remained are indicated by circles. The number

670
in circles and the size of the circles indicate the total number of participants remaining at the location for the measurement period.

The lines indicating movement paths on the map are thicker, the greater the number of participants moving along the lines.

The measurement areas in Fukushima are mainly locations where the participants stayed: Fukushima city, Koriyama city, Minamisoma city, Tomioka town, and Iwaki city. The measurement areas in the Greater Tokyo Metropolitan area are mainly locations where the participants stayed in Tokyo.
2.2. Measurement method

Exposure includes internal exposure (inhalation, ingestion, injection and absorption) as well as external exposure. There are several reports on the relationship between internal and external exposures in Fukushima [11, 22, 23].

Harada et al investigated on internal exposure in three municipalities in Fukushima prefecture in 2012 [23]. This report compared internal exposures by food intake and by breath inhalation with external exposure measured by personal dosimeter. According to this report, internal exposure was two orders of magnitude lower than external exposure. They also reported that internal exposure by inhalation was considerably lower than that by food intake. Therefore, the internal exposure in Fukushima is not considered to be as large as the external exposure. Internal exposure is out of the scope of this paper.

For a maximum period of six days including non-workdays over the period from November 2018 until March 2019, the participants were instructed to continuously wear a personal dosimeter on their chest from the time they woke up until they went to bed as well as to carry a GPS logger, except when sleeping or bathing, in order to measure their individual dose during daily activities.

The measurement instruments were a personal dosimeter manufactured by Fuji Electric Co., Ltd. (DOSEe nano) and a GPS logger manufactured by ARKNAV International (K18U) (figure 4).

The DOSEe nano personal dosimeter measures a 1 cm personal dose equivalent and has the capability to record in the device’s internal memory a log of the results up to a maximum of 9000 measurements during each one-minute interval (table 2).

The GPS logger uses United States satellite tracking and has the capability to take measurements for a period of approximately five months with the recording function set at one-second intervals (table 3).

For measuring individual doses, the personal dosimeters were set to record at one-minute intervals and the GPS loggers at five-second intervals.

The air dose rate at measuring locations used the air dose rate from the 13th airborne monitoring survey conducted by the Nuclear Regulation Authority [3]. The survey used airborne monitoring to measure air dose rates on 15 November 2018 and the results were published by the Japanese government on 8 March 2019. The weathering effect was about 0.4% when
the dose rate was compared at given points. Even though nine years have passed since the earthquake, the weathering effect is regarded as having been small. In this paper, the airborne monitoring measured values were adjusted to the dose on the date measured, taking into consideration physical attenuation of Cs-134 and Cs-137.

It was decided that the place where a participant was at 0:00 AM was the participant’s home. To analyse the relation between the individual external doses and their activities, it was necessary to determine whether the location where the individuals were at was indoors or outdoors with the exception of when they were at home. In cases where the participant remained at one location after GPS data transit, the extent of the change in the individual external dose was verified. In cases where the individual external dose was below 95% of average dose in transit, it was determined that the participant was indoors, and cases where there was above 95% of average dose in transit to be ones where the participant was outdoors.

The 95% threshold was determined as follows.

From 1 September 2018 to 31 August 2019, the TEPCO employee used the same dosimeter and GPS to measure his individual external dose every day. While these measurements were being take, the employee recorded his activities in detail. This record was regarded as the correct description of the employees’ activities. Then, using the data obtained from the personal dosimeter and GPS, a determination was made as to when the employee was outdoors and when he was indoors. Those determinations were then compared to the detailed records produced by the employee of his activities. It was found that the highest percentage of correct answers for indoor/outdoor determination resulted in a threshold of 95%.

Although we did not verify whether any participants were engaged in unusual work patterns, they were asked to measure their individual external doses over the course of their normal daily routine activities. As such, the measurement results are not completely out of the norm.

Extraordinary data due to radio waves were excluded from the data set and regarded as noise.
The 63 participants who recorded their activities also had GPS loggers. The effectiveness of GPS in determining activities was confirmed by comparing the participants’ activity records and GPS records.

2.3. Estimation of individual external dose

Individual external doses took into consideration the difference between workdays and non-workdays. The annual individual external dose was calculated by using equation (1) to multiply the number of workdays and non-workdays respectively by the average individual external dose per workday and the average individual dose per non-workday. The annual additional individual external dose was calculated using equation (2) where 0.33 mSv y\(^{-1}\), the annual natural background dose as reported by the Nuclear Safety Research Association, is subtracted from the annual individual external dose [24].

\[
\text{Annual individual external dose} = \text{Individual external dose per workday (average)} \times (5\text{days} \times 52\text{weeks} + 1\text{day}) + \text{Individual external dose per non workers (average)} \times 2\text{days} \times 52\text{weeks}
\]

\[
\text{Annual additional individual external dose (measured)} = \text{annual individual external dose} - 0.33\text{mSv y}^{-1}, \text{annual natural background dose}
\]

3. Results

The estimated results for the annual additional individual external dose of 238 participants, for which there were individual dose results for workdays and non-workdays, were between 0.07 and 2.13 mSv y\(^{-1}\) (figure 5). The average of participants in Fukushima prefecture was 0.33 mSv y\(^{-1}\) and the median was 0.26 mSv y\(^{-1}\). 97.5% of the 112 indoor workers and 126 outdoor workers had an annual additional individual external dose of less than 1 mSv y\(^{-1}\), and most of the indoor workers had an annual additional individual external dose of 0.5 mSv y\(^{-1}\) or less. The six people whose annual additional individual external dose exceeded 1 mSv y\(^{-1}\) were workers in restricted access zones and the highest annual additional individual external dose was 2.13 mSv y\(^{-1}\).

Employees are provided 20 paid holidays annually and there are approximately 20 national holidays in Japan each year. The impact of holidays upon equation (1) was considered. The annual individual external doses were recalculated using equation (1) for a case where there are 20 holidays (paid) and one where there are 40 holidays (paid and national). Figure 6 shows the distribution of annual additional individual external dose (measured) for each case. The doses sustained by indoor workers changed little due to the increase in holidays. The maximum doses sustained by outdoor workers decreased slightly due to the increase in holidays. However, the medians in each case were almost same. It was found that there was little change in the annual additional individual external dose trend.

In some municipalities in Fukushima prefecture, external individual doses have been carried out for the citizens [6, 7]. For example, in Minamisoma city, glass badges were handed out to citizens, and measurements of 4799 people during the three months of January-March.
Figure 5. Distribution of the number of participants according to annual additional individual external dose.

Figure 6. Distribution of annual additional individual external dose (measured) in three cases of the number of holidays. Note: In the box-and-whisker plot, the bottom and top of the box are the 5th and 95th percentiles respectively, and the band inside the box is the median (50th). The upper ends (bottom ends) of the whiskers indicate the maximum (minimum) values.
in 2019 showed an average of 0.08 mSv of additional individual external dose. This was an annual additional individual external dose of 0.32 mSv. Overall, 98.2% of people had an annual additional individual external dose of less than 1 mSv [7]. As compared to the data measured in this paper, there was a common trend that most of the participants had an annual additional individual external dose of less than 1 mSv.

The measurements in this paper covered the entire Fukushima prefecture and were measured by TEPCO employees who work in areas with relatively high air dose rates. Although the measurement methods were different too, similar trends were obtained for the measurement results of citizens in Minamisoma. It was believed that the data in this paper was meaningful in providing the current situation of external exposure in Fukushima prefecture.

The annual additional individual external doses were estimated using equation (3) [25]. The air dose rate at home used the air dose rate from airborne monitoring. Equation (3) assumes that the participant remains 8 h outside and 16 h inside a wooden house. The straight line in figure 7 is the value calculated using equation (3). The outdoor dose rate in equation (3) assumes the air dose rate in the participant’s home. In figure 7, the annual additional individual external doses measured by personal dosimeter were plotted with the air dose rate at home from airborne monitoring. Measured doses tended to be lower than the value calculated using equation (3). The annual additional individual external doses of several outdoor workers were higher than the rate calculated using equation (3). These outdoor workers worked outside in the areas where air dose rates were relatively high. This may also have been a reason why the air dose rates in their homes were low.

\[
\text{Annual additional individual external dose (estimated)} = (\text{outdoor air dose rate} - \text{natural background dose rate}) \times 8\text{hr} + \text{reduction factor (Equation 4: wooden house = 0.4)} \times (\text{outdoor air dose rate} - \text{natural background dose rate}) \times 16\text{hr}) \times 365\text{days} \quad (3)
\]

The deviation between measured and calculated values was due to differences in air dose rate, type of building, estimated air dose rate, activity pattern, and area of activity. This shows why it is important to take actual measurements.

4. Discussion

Several compound elements are involved in the model used for estimating individual external dose, such as the relationship between air dose rate and individual external dose in equation (3), activity patterns, ratio of time spent at indoor or outdoor locations, and reduction factor for indoor dose rate against outdoor dose rate.

Using these measurements, we analysed the actual state of these elements and differences.

4.1. Air dose rate and individual external dose

It has been reported that the individual dose as measured for an adult is 0.7 times the ambient dose equivalent in conditions where there is radiation exposure from all directions [26, 27].

To verify this ratio, the air dose rate and the individual external dose were measured at 28 points within the measurement area in Fukushima prefecture. The measurement area in Fukushima prefecture was divided by air dose rate by 0.1 \(\mu\text{Sv h}^{-1}\) increments from 0 to 0.5 \(\mu\text{Sv h}^{-1}\) and above 0.5 \(\mu\text{Sv h}^{-1}\). The air dose rates were taken around five points selected from each of these specific areas for a total of 28 points. The air dose rates above ground
Figure 7. Relationship between the air dose rate at participant’s home from airborne monitoring and the annual additional individual external dose.
were measured at a height of 1 m above ground at 28 points. The instrument used for measuring the air dose rate above ground was the Hitachi-Aloka Medical Scintillation Survey Meter (TCS-172B).

Figure 8 shows a graph plotting measured air dose rates above ground along the horizontal axis and the individual external dose per hour at the same place along the vertical axis. Based upon these results, it was confirmed that the individual external dose per hour was approximately 0.7 times the air dose rate. 0.7 was used as the conversion coefficient to calculate the air dose rate from the individual external dose in below.

4.2. Air dose rate from airborne monitoring

The air dose rate above ground is often used for estimating individual external dose. Because the area where measurements of the air dose rate above ground are possible are limited, it is considered to use the results of airborne monitoring covering the entire area. The relationship between the air dose rate from airborne monitoring and above ground were verified.

The air dose rate above ground and the air dose rate from airborne monitoring are positively correlated and the ratio between the two is said to be within a range of 0.5 to 1.5 [28]. But the environment changes due to decontamination, weathering, resuming a daily life by revitalisation, and other factors. The air dose rate above ground were measured at 28 points. In comparison between the air dose rate from airborne monitoring and above ground, it was found that the air dose rate above ground was between 0.2 and 1 times the air dose rate from airborne monitoring (figure 9).

Figure 8. Relationship between measured air dose rate and measured individual external dose.
4.3. Individual external doses and the activity patterns

The ratio of time spent indoors and outdoors was investigated for the 277 participants who worked indoors and outdoors in Fukushima Prefecture.

4.3.1. Indoor workers’ individual external doses and activity patterns. The activity patterns and daily individual external doses of the 127 indoor workers were investigated.

The activity patterns were classified into four categories: home indicating that a participant was at home, indoor indicating that a participant was inside a building other than his or her home, outdoor indicating that a participant was outside a building, and moving indicating that a participant was moving by car or other means.

The sums of number of times and individual external doses for each participant were calculated for each of these four activities. These data were converted into a per day (24-hour) unit.

Figure 10 shows the averages of times and doses for all indoor workers’ data.

The average times (individual external doses) per day for each activity were 15.6 h (1.03 μSv) for time spent at home, 7.1 h (0.38 μSv) for time spent indoors, 0.3 h (0.02 μSv) for time spent outdoors, and 1.0 h (0.08 μSv) for time spent moving. It was found that 22.7 h
(1.41 µSv) were spent inside structures (at home and indoors), and 1.3 h (0.10 µSv) spent outside structures (outdoors and moving) (figure 10).

Next, the median values were taken into consideration to confirm statistical dispersion. The box and whisker plots in figures 11 and 12 show the distribution of times and individual external doses for the four activities based on all indoor workers’ data. The median values are shown in the figures.

The median times were 15.7 h (0.99 µSv) for time spent at home, 6.9 h (0.38 µSv) for time spent indoors, 0.1 h (0.01 µSv) for time spent outdoors, and 1.0 h (0.07 µSv) for time spent moving. It was found that 22.9 h (1.37 µSv) were spent inside structures (at home and indoors) and 1.1 h (0.08 µSv) spent outside structures (outdoors and moving) (figures 11 and 12).
Figure 12. Distribution of individual external doses per day for each activity for indoor workers. Note: In the box-and-whisker plot, the bottom and top of the box are the 5th and 95th percentiles (box) respectively, and the band inside the box is the median (50th). The upper ends (bottom ends) of the whiskers indicate the maximum (minimum) values.
4.3.2. Outdoor workers’ individual external doses and activity patterns. The daily activity patterns and individual external doses of the 150 outdoor workers were investigated. Figure 13 shows the averages of the times and doses for all outdoor workers’ data.

The average times (individual external doses) per day of each activity pattern were 14.5 h (0.97 μSv) for time spent at home, 4.8 h (0.33 μSv) for time spent indoors, 2.5 h (0.69 μSv) for time spent outdoors, and 2.2 h (0.30 μSv) for time spent moving. It was found that 19.3 h (1.30 μSv) were spent inside structures (home and indoors), and 4.7 h (0.99 μSv) were spent outside structures (outdoor and moving) (figure 13).

The box and whisker plots in figures 14 and 15 show the distribution of times and individual external doses for the four activities based on all outdoor workers’ data. The median values are shown in the figures.

The median times were 14.3 h (0.93 μSv) for time spent at home, 4.6 h (0.31 μSv) for time spent indoors, 2.2 h (0.30 μSv) for time spent outdoors, and 2.0 h (0.25 μSv) for time spent moving. It was found that 19.6 h (1.27 μSv) were spent inside structures (home and indoors) and 4.4 h (0.60 μSv) spent outside structures (outdoors and moving) (figures 14 and 15).

The average times (individual external doses) per day spent in each activity pattern for the 27 outdoor workers, for whom there were records of their activities allowing for more accurate analysis, were investigated. It was found an average of 19.3 h (1.32 μSv) was spent inside...
structures and 4.7 h (0.66 μSv) spent outside structures. For outdoor workers, these results, which were based upon the activity records, indicated the same trends as those based upon GPS data. The times (individual external doses) per day spent in each activity pattern for 150 outdoor workers based upon GPS data may be regarded as valid.

The daily times and individual external dose outside structures for outdoor workers were higher than those for indoor workers. It was found that the time that participants spent outdoor was shorter than the time used for estimating the annual individual external dose (8 h day⁻¹), and the time spent indoor was longer than 16 h day⁻¹.
The dose rates calculated from the individual external dose and time indicate the value in accordance with the air dose rate during each activity. The dose rates of indoor workers while engaged in outdoor activity was 0.07 $\mu$Sv h$^{-1}$ as shown in figure 10. The dose rate of outdoor workers was 0.28 $\mu$Sv h$^{-1}$ as shown in figure 13. There was a large difference in the outdoor activities of indoor workers and those of outdoor workers. Indoor workers mostly performed desk work in an office. Indoor workers would work outdoors where the air dose rate was low and decontamination activities had already been completed. Outdoor workers mainly worked outside performing field management, dose surveys, or weeding work in areas where the air dose rate was relatively high. The dose rates based on figures 10 and 13 corresponded to such conditions.

4.4. Reduction factor

The reduction factor used in equation (3) was defined as the ratio of the indoor air dose rate to the outdoor air dose rate (equation (4)).

The reduction factor for indoors varies depending upon the structure, material, dimensions, and other characteristics of the building, and is affected by the measurement points for air dose rates indoor and outdoor. Assessments of the reduction factor have been reported in case studies by the Japan Atomic Energy Agency and others [29–33].

$$\text{Reduction factor} = \frac{\text{Indoor air dose rate excluding natural background dose rate}}{\text{Outdoor air dose rate excluding natural background dose rate}}$$

$$= \frac{\text{Indoor air dose rate} - 0.04}{\text{Outdoor air dose rate} - 0.04}$$

(4)

For example, concrete structures have greater shielding capability than wooden structures. Therefore, the reduction factor is 0.4 for wooden structures and 0.2 for concrete structures. The reduction factor values reported here might be assessed using the air dose rate prior to decontamination. These data may have been measured under conditions different from current environmental conditions, so the following attempt was made to estimate the reduction factor.

GPS data was used to automatically determine the location of the participant’s home. The location where the participant was at 0:00 AM is defined as the location of participant’s home. The indoor and outdoor air dose rates in all participants’ homes could not be measured. So, the indoor air dose rate for the home was calculated based on the individual external dose using a conversion coefficient of 0.7. The air dose rate from airborne monitoring was used as the outdoor air dose rate at the location of the participant’s home (equation (5)).

$$\text{Reduction factor} = \frac{\text{Indoor individual external dose per hour/conversion coefficient - natural background dose rate}}{\text{Outdoor air dose rate by airborne monitoring - natural background dose rate}}$$

$$= \frac{\text{Indoor individual external dose per hour} / 0.7 - 0.04}{\text{Outdoor air dose rate by airborne monitoring} - 0.04}$$

(5)

The relationship between the outdoor air dose rate at each participant’s home and the reduction factor is presented in figure 16. Natural background dose is subtracted from the outdoor air dose rate.

The reduction factor tended to be higher than for wooden structures (0.4) or concrete structures (0.2) and tended to be higher in the range of low air dose rates. It is conceivable that this is due to multiple factors. One of the primary considerations is that personal dosimeters were not worn at home.

In order to correctly measure individual dose, the personal dosimeter needs to be worn on the participant’s chest. However, it was possible that many participants did not wear their personal dosimeters at home, such as when it was being recharged or while the participant was bathing or sleeping. It was difficult to determine accurately from the data whether participants removed their dosimeter or not. The reduction factor was analysed on the assumption that
Figure 16. Relationship between outdoor air dose rate at each participant’s home and reduction factors.
Figure 17. Distribution of the individual external doses when personal dosimeter worn and when not worn. Note: In the box-and-whisker plot, the bottom and top of the box are the 5th and 95th percentiles (box) respectively, and the band inside the box is the median (50th). The upper ends (bottom ends) of the whiskers indicate the maximum (minimum) value.

Participants did not wear their dosimeters at home. The effect was considered of wearing a dosimeter upon the reduction factor.

Additional research by the National Institute of Radiological Sciences and Japan Atomic Energy Agency reported on the directional characteristics of personal dosimeters in relation to $\gamma$ rays [27]. It was reported that the measured value without a phantom was 1.2 times the measured value with a phantom. (equation (6))

$$\text{Individual external dose when not wearing personal dosimeter} = \text{Individual external dose when wearing personal dosimeter} \times 1.2 \quad (6)$$

The individual external doses measured when participants were wearing personal dosimeters were compared with doses measured when they were not wearing personal dosimeters at home. Eleven participants measured the individual external doses for 30 min when the personal dosimeter was worn and when it not worn at a residence in Fukushima city. The individual external dose when the personal dosimeter was not worn was 1.17 to 1.59 times (median 1.35 times) that of when the personal dosimeter was worn (figure 17). It was assumed that the individual external doses increased owing to loss of body shielding as compared to when the personal dosimeter was worn.

Based upon this result, the data provided in reference [27] was used and the individual external dose measured when not wearing a personal dosimeter was assumed to be 1.2 times that when wearing one. So, the following equation was used to find the indoor air dose rate using the individual external dose data for when the participants were at home.

$$\text{Indoor air dose rate} = \frac{\text{measured individual external dose per hour at home}}{1.2/0.7} \quad (7)$$

Figure 18 shows the relationship between the outdoor air dose rate from airborne monitoring and the revised reduction factor from equations 4 and 7. As a result, there were fewer cases
Reduction factor for wooden structures: 0.4
Reduction factor for concrete structures: 0.2
(air dose rate from airborne monitoring $\mu$Sv/h)

Outdoor air dose rate excluding the natural background dose rate ($\mu$Sv/h)

Figure 18. Relationship between the outdoor air dose rate and revised reduction factor.
where the reduction factor exceeded 1.0. Figure 19 shows the distribution of the reduction factors. The reduction factor median was 0.34, and the 75th percentile was 0.45. 70% of the reduction factors ranged from 0.2 to 0.5 as shown in figure 19. 2% of the reduction factors were distributed around 1.0.

It was estimated that participants rarely wore their personal dosimeters at home. On the assumption that participants did not wear dosimeters at home, we considered the reduction factor. Figure 16 shows data for times when personal dosimeters were not worn at home. Figure 18 shows data for times when participants wore personal dosimeters at home. Therefore, the reduction factors in figure 18 were lower, because they were corrected by taking into consideration the air dose rate at home.

As concerns individual external dose measurement, it was estimated that many participants did not wear personal dosimeters at home. Therefore, it was presumed that the actual individual external doses were lower than the measured individual external doses.

The factors influencing the reduction factor were considered.

A first factor is the position at which the air dose rate is measured indoors and outdoors. The air dose rate indoors is higher closer to windows and lower near the center of the building. Building dimensions have an effect on the indoor air dose rate. The outdoor air dose rate is affected by the distance from buildings and decontamination condition.

A second factor is the impact of natural radiation. Natural radiation is present both indoors and outdoors. The impact of natural radiation is more significant at lower air dose rates. The effect of natural radiation was removed using the reduction factor formula and can be ignored in the analysis of figures 16 and 18.

A third factor is the impact of indoor radiation sources. However, this factor is admissible under limited conditions.

A fourth factor is the use status of the dosimeter at home. This factor is specifically included in our measurements.
Various factors complicate the understanding the reduction factor. In our study, it was found that there were many variable factors in the model for estimating individual external dose.

5. Conclusions

The DOSEe nano personal dosimeter and GPS logger were used to measure and assess the individual external doses of 293 employees of Tokyo Electric Power Company Holdings, Inc. The areas where the employees worked in Fukushima Prefecture are Fukushima city, Koriyama city, Minamisoma city, Tomioka town, and Iwaki city. The annual additional individual external dose of the participants, which was estimated based upon measured individual external doses, was below 1 mSv and even 0.5 mSv or less in many cases. The number of participants who exceeded the annual additional individual external dose of 1mSv was six outdoor workers. These employees work in restricted access zones and other areas. The median for all outdoor workers including these six workers was 0.34mSv. The median for indoor workers was 0.21mSv. The doses of all indoor workers were below 0.6mSv.

Having taken into account the change in the air dose rate from the time of the accident up until the present, these measuring results suggest that annual additional individual external doses have decreased as the air dose rate has fallen due to decontamination and weathering.

The measured individual external doses were lower than the calculated individual external doses using the model (equation (3)) that is based upon the air dose rate from airborne monitoring.

First, the participant’s home was used as the reference point for the air dose rate in equation (3) of the model. Although it is an approximation, it is important to use the air dose rate corresponding to the scope of the area where the activity took place.

The conversion coefficient (ratio of individual external dose to air dose rate) was verified based upon actual measurements of air dose rates and individual doses at 28 points. It was found to be 0.7, which is the same as has been reported [26, 27]. Therefore, it was presumed that the actual individual external doses were lower than the individual external dose based upon equation (3) of the model.

The time spent in activity patterns during the day by the 277 participants working in Fukushima Prefecture were investigated. It was found that 19 or more hours were spent indoors, which is longer than the 16 h estimated using equation (3). Based on this, it was presumed that the actual individual external doses were also lower than the individual external dose based upon equation (3) of the model.

It was estimated that many participants did not wear personal dosimeters at home. If participants did not wear a personal dosimeter for a long time, the actual individual external dose may be lower than the measured value.

The reduction factor for home was found to be a little less than 0.5 and tended to be higher at lower air doses. It was found that various factors complicated the understanding of the reduction factor.

The results of this investigation have clarified the relationship between individual external dose and air dose rate, relationship between the air dose rate from airborne monitoring and air dose rate measured above ground, the ratio of the time and individual external dose for each activity pattern during a day, and differences in the reduction factor in homes. These results verified that values measured with personal dosimeters tend to be lower than the results of estimates formulated based upon activity patterns, spending 8 h outdoors and 16 h indoors a day, and the air dose rate from airborne monitoring using equation 3.
Although it is important to construct a model of activities and estimate individual external doses based on a representative air dose rate, it also is important to monitor and take actual measurements. In addition, it is necessary to analyse the difference between model results and measured data.

In this paper, we used actual measurements and analysed the results to conduct an initial investigation into the actual state of individual external doses.

There are many problems are present when considering individual external dose measurement. Nevertheless, it is important to use individual external dose measurements to understand actual circumstances.

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