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An influential factor for external radiation dose estimation for residents after the Fukushima Daiichi Nuclear Power Plant accident - Time spent outdoors for residents in Iitate Village -

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Keywords: nuclear accident, external dose, time spent outdoors, Iitate Village

ABSTRACT

Many studies have been conducted on radiation doses to residents after the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident. Time spent outdoors is an influential factor for external dose estimation. Since little information was available on actual time spent outdoors for residents, different values of average time spent outdoors per day have been used in dose estimation studies on the FDNPP accident. The most conservative value of 24 hours was sometimes used, while 2.4 h was adopted for indoor workers in the UNSCEAR 2013 report. Fukushima Medical University has been estimating individual external doses received by residents as a part of the Fukushima Health Management Survey by collecting information on the records of moves and activities (the Basic Survey) after the accident from each resident. In the present study, these records were analyzed to estimate an average time spent outdoors per day. As an example, in Iitate Village, its arithmetic mean was 2.08 h (95% CI: 1.64-2.51) for a total of 170 persons selected from respondents to the Basic Survey. This is a much smaller value than commonly assumed. When 2.08 h is used for the external dose estimation, the dose is about 25% (23-26% when using the above 95% CI) less compared with the dose estimated for the commonly used value of 8 h.

1. Introduction

Many studies have been conducted on radiation doses to residents after the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident [1, 2]. Common approaches to estimate external dose are: (1) using personal dosimeters, (2) in-situ measurements (or model calculations) of gamma ray dose rate at selected places followed by estimation of personal dose assuming time spent indoors and outdoors at those places. For the latter approach, an assumption typically adopted for the daily time budget (time spent indoors and outdoors per day) was that people spend 8 hours outdoors and 16 hours indoors [3, 4]. The Japanese government's dose estimation method also employs the same assumption. However, another assumption that people stayed outdoors all day long is used to estimate "projected dose", which is defined as the dose received if no protection measures are taken [5]. The assumption is clearly conservative and the resulting doses are overestimated. On the other hand, the UNSCEAR 2013 report [6] estimated an occupancy factor for outdoors as 0.1 for indoor workers (spending 2.4 hours outdoors).

The average time spent outdoors per day is an influential factor for estimating external doses, because external dose indoors is considered to be reduced by more than 60% compared with the dose without shielding (outdoors) in a ground-shine geometry with

radionuclides deposited on the ground [7].

Fukushima Medical University has been conducting a survey to estimate individual external doses for the first four months after the accident (Basic Survey) [7-9]. Since personal dosimeters were not generally available soon after the accident [10], the following approach was used to estimate the four-month external doses in the Basic Survey: (1) estimating daily ambient gamma ray dose rate for all of Fukushima Prefecture by dividing it into divisions with a 2 km × 2 km mesh, (2) collecting information on personal behaviors including moves, daily time budget (indoors or outdoors) and dwelling types where each person stayed by using self-administered questionnaires and (3) superimposing digitized records of moves and activities on the daily gamma ray dose rate maps by a computer program [7]. The questionnaire used for the Basic Survey was designed to ask about the behavior for each day in 2011 from March 11 to July 11, targeting all residents of Fukushima Prefecture (around 2.05 million persons).

Iitate Village is located outside the 20-km radius zone around the FDNPP (the village is about 30-45 km northwest of the plant (figure 1) [11]. At some time after the evacuation instruction was issued to persons within the 20-km radius, it was found that Iitate Village was likely to be a hotspot area. On April 22, 2011, because there was a threat that the estimated dose could reach 20 mSv one year after the accident, it was requested that residents and other persons evacuate to other areas within roughly one month [12]. Around 30% of the residents still remained at the end of May, but the percentage decreased to around 10% at the end of June 2011 [13].

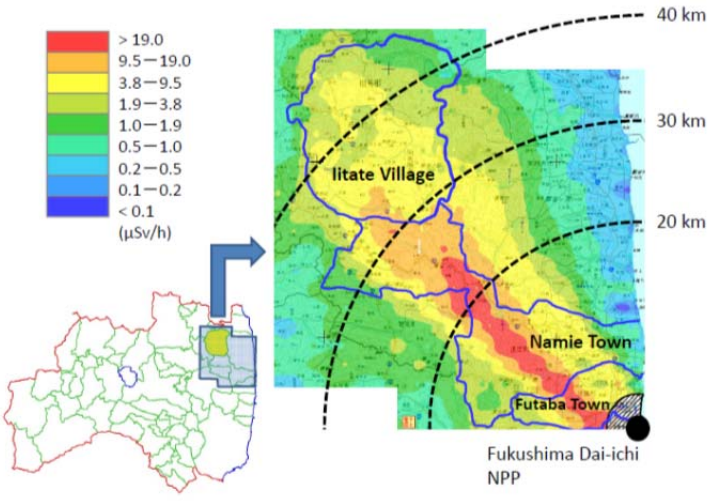


Figure 1. Location of Iitate Village and its gamma ray dose rate level. The gamma ray dose rate map was modified from maps obtained by airborne monitoring surveys made in April to June 2012. [11] Decay correction was made to June 28, 2012.

Gamma ray dose rate at Iitate Village office has been continuously measured since March 14, 2011. It jumped to the maximum value of 45 μSv/h at 18:20 on March 15, 2011,but at the end of March this had decreased considerably to around 7 μSv/h due to decay of short-lived radionuclides. By the end of July, it had gradually decreased to around 2.5 μSv/h [9]. This gamma ray dose rate is lower compared with rates for municipalities within the 20-km radius (Namie Town, Futaba Town, etc.), as shown in figure 1. However, due to the delayed instruction to evacuate, the external doses to residents in Iitate Village were generally higher than those for residents in municipalities within the 20-km radius [14].

Imanaka et al. [15] estimated initial external doses for residents in Iitate Village. The average dose by their estimation was reported to be 7.0 mSv as the external dose from March 11 to July 31 [16]. On the other hand, a distribution of the four-month individual doses for respondents from Iitate Village (n=2,331) to the Basic Survey is shown in figure 2 [14]. The average individual dose for these respondents was 4.0 mSv. One of the reasons for the difference could be the daily time budget used for dose calculation in [14] and [16]. Thus, the average time spent outdoors per day and the dwelling types were analyzed for randomly selected responses to the Basic Survey and their effects on external dose were discussed.

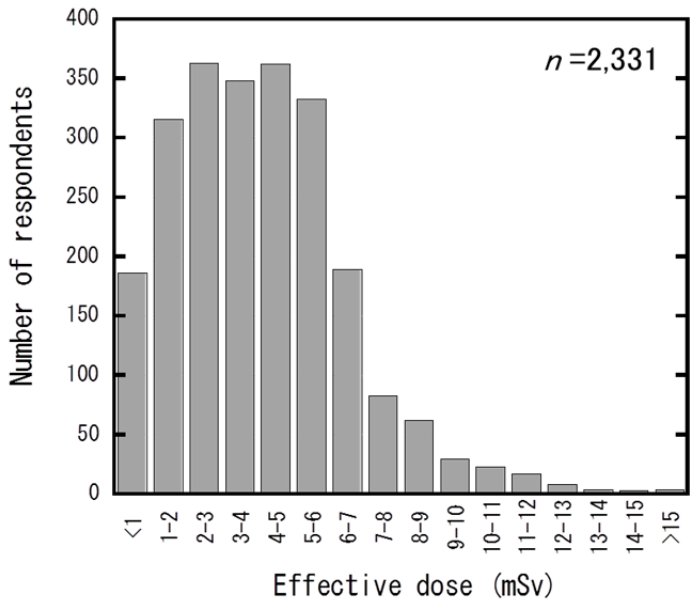


Figure 2. Distribution of the four-month individual doses for respondents from Iitate Village to the Basic Survey.

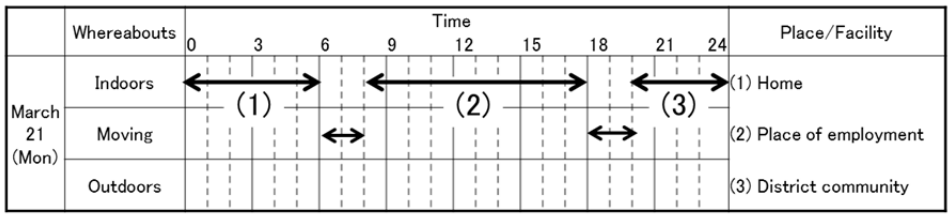
2. Materials and methods

2.1 *Questionnaire for the Basic Survey*

Details of the Basic Survey are described elsewhere [9]. The study protocol of the Basic Survey was reviewed and approved by the Ethics Review Committee of Fukushima Medical University. The study was conducted in accordance with the approved guidelines.

The questionnaire was prepared to ask about behavior for each day in the four-month period from March 11 to July 11, 2011. The self-administered questionnaire was mailed to each resident to collect information on his/her dwelling place, places visited, time spent indoors and outdoors, and time of moves during the period. The questionnaire form for the period from March 11 to March 25 is shown in figure 3 (a). For the later period to July 11, a simpler form was used. The handwritten forms were converted to digitized forms for calculation by a computer program. Figure 3 (b) shows an example of the digitized questionnaire form.

(a)



(b)

	Place (1)					Place (2)						
Date	Address at the beginnng of day	Longitude	Latitude	Type of building (Place 1)		Address of Place (2)	Longitude	Latitude	Time for moving (Place 1 to 2)	Type of building (Place 2)	Time spent indoors (Place 2)	Time spent outdoors (Place 2)
March 21, 2011	XXX	37.7	140.7	1		YYY	37.6	139.6	2	1	10	0

	Place (3)						
Address of Place (3)	Longitude	Latitude	Time for moving (Place 2 to 3)	Type of building (Place 3)	Time spent indoors (Place 3)	Time spent outdoors (Place 3)
ZZZ	36.8	139.8	2	1	4	0

Figure 3. A sample of records of moves and activities on a response sheet of the Basic Survey (a) and their digitized form (b).

For children of elementary school age or younger, their parents were asked to fill in the form instead. Also, for children under the age of 20, parents were asked to sign the questionnaire and verify the information. After filling out the form, respondents were

asked to mail it back. Sending questionnaires to the residents was started in June 2011 and finished in October 2011. Efforts to collect the responses continue to be made and responses were still being mailed back even in 2015.

There were some responses for which records of behavior data were less than four months for unknown reasons. For most such cases, the behavior records corresponding to March 11 through some point before July 11 were filled in.

2.2 *Random sampling of responses to the questionnaire*

In total, about 3,400 responses to the questionnaire of the Basic Survey had been collected from residents in Iitate Village and the response rate as of September 30, 2015 was around 52% [14]. In accordance with the distribution of the original population by age group, a total of 240 responses were randomly selected from the collected responses in the following way. In the selection process, it was not checked whether two or more respondents were selected from the same family. Nine age groups were considered. For age groups of 0-9y, 10-19y, 20-29y, 30-39y, 40-49y, and > 80y, 10 males and 10 females were selected from each age group. For age groups of 50-59y, 60-69y, and 70-79y, 20 males and 20 females were selected from each one. This was almost in accordance with the original age distribution of residents of Iitate Village. Although the random sampling was made in February 2014, the number of total responses at that time was almost the same as the latest number.

The behavior data were analyzed for the 240 selected respondents to estimate time spent outdoors and building type of their own houses (wooden, concrete, etc.). Building types for dwellings where residents stayed temporarily (e.g. place of employment, evacuation center, etc.) were not considered. Responses for which periods with records of behavior data were less than four months were analyzed until the last date of the records and there were 70 of these data sets among the 240 selected.

2.3 *Estimation of average time spent outdoors per day*

The average time spent outdoors during the stay in Iitate Village was estimated from each response. Some evacuees came back to Iitate Village again before July 11, 2011 after temporarily evacuating to another municipality. In such cases, their second (or more) stay(s) in Iitate Village were included for the analysis.

Average time spent outdoors per day during the stay in Iitate Village A_o (h) is calculated as follows:

$$A_o = 24 \times T_o / T_t \qquad (1)$$

where T_o (h) is the accumulated time spent outdoors during the stay in Iitate Village and T_t (h) is the accumulated time of stay (outdoors, indoors and moving) in Iitate Village. Although time for moving within Iitate Village was included in T_t, time for moving from Iitate Village to another municipality and vice versa were not included in T_t. As seen in the example digitized form of figure 3 (b), when the address of Place (2) was located outside of Iitate Village, the time for moving from Place (1) (in Iitate Village) to Place (2) (2 hours) was not included in T_t.

Effects of A_o on external dose can be considered as the dose rate ratio of these subjects to those who stayed outdoors for 24 hours a day at a place (the most conservative assumption) as a standard. The dose (D) corresponding to a different time spent outdoors at the same place is calculated by:

$$D = t_o/24 + 0.4 \times t_{in}/24, \ (t_o + t_{in} = 24) \qquad (2)$$

where t_o is the time spent outdoors per day (h), t_{in} is the time spent indoors per day (h) and 0.4 is the dose reduction factor for wooden houses. In the case of staying outdoors for 24 hours a day, D is equal to 1.

3. Results

3.1 *Analysis of average time spent outdoors per day*

The average time spent outdoors per day during the stay in Iitate Village (A_o) was estimated for each of the 240 persons on the basis of Eq. (1). Its frequency distribution is shown in figure 4. The arithmetic mean was 2.01 h (95% CI: 1.93-2.10 h) with a range of 0 to 15.5 h. The median was 0.94 h. The distribution for A_o by age group is shown as figure 5. It was higher in the middle aged groups than the others. The median for A_o for age groups of >80y was 0.085 h and that for age groups of 0-9y and 10-19y was zero. Almost half of the responses from these age groups indicated that their activities during the stay in Iitate Village were limited to being indoors and moves. Although it might not be true, the analysis was faithfully based on the behavior records of each individual's responses. Furthermore, some of the responses indicated that a part of the residents moved from Iitate Village almost immediately after the earthquake without spending any time outdoors in Iitate Village.

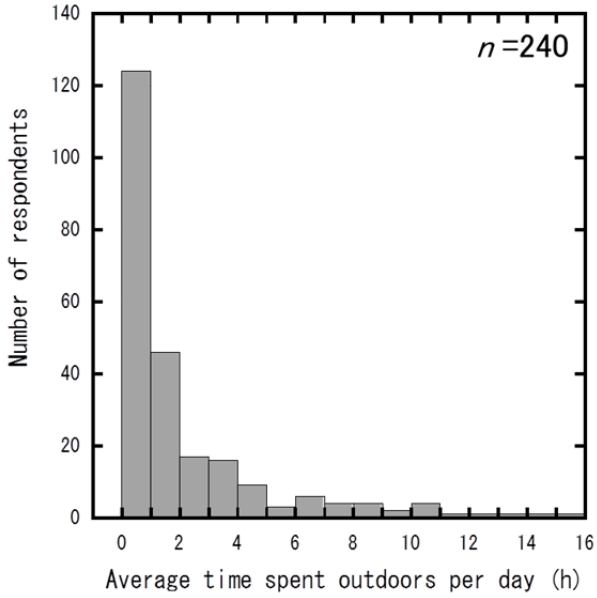


Figure 4. The distribution of average time spent outdoors (A_o) for all respondents (n=240).

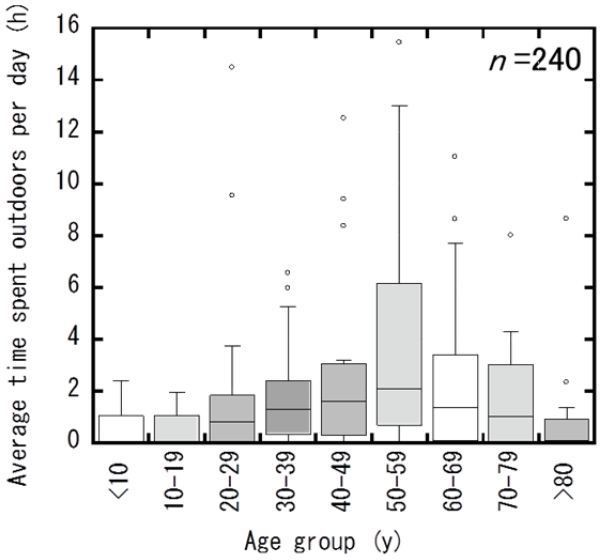


Figure 5. The difference in average time spent outdoors (A_o) by age group (n=240).

Although the questionnaire did not ask about occupations, the increased time in the middle age groups may be due to more outdoor workers among the groups. A difference in A_o by gender is demonstrated in figure 6 which categorized males and females into three age groups (<20y, 20-59y and >60y). For age groups of <20y and >60y, the difference of median values by gender were not significant (Wilcoxon test, p=0.68 and 0.15). On the other hand, it was significant for the age group of 20-59y (Wilcoxon test,

p<0.001). This might be due to inclusion of most outdoor workers as males in the 20-59y group.

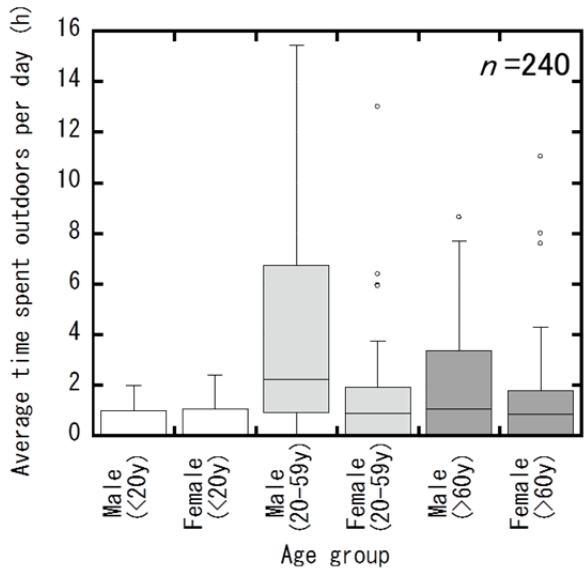


Figure 6. The difference in average time spent outdoors (A_o) by gender (n=240).

As mentioned before, there were some responses for which records of behavior data were less than four months for unknown reasons. In such cases, the behavior data were analyzed until the last date of the records. The average time spent outdoors per day during the stay in Iitate Village (A_o) was also estimated only for persons who had four-month behavior records (n=170). The distribution of A_o for these 170 persons is shown in figure 7 (arithmetic mean, 2.08 h (95% CI: 1.64-2.51 h); median, 0.99 h; range, 0 to 14.5 h). The same statistical parameters for 70 persons with records of less than four months were as follows: arithmetic mean, 1.86 h (95% CI: 1.16-2.56 h); median, 0.79 h; range, 0 to 15.5 h. Although A_o for the 70 persons was slightly smaller than that for 170 persons with four-month records, there was no significant difference in median values between the two groups (Wilcoxon test, p=0.45).

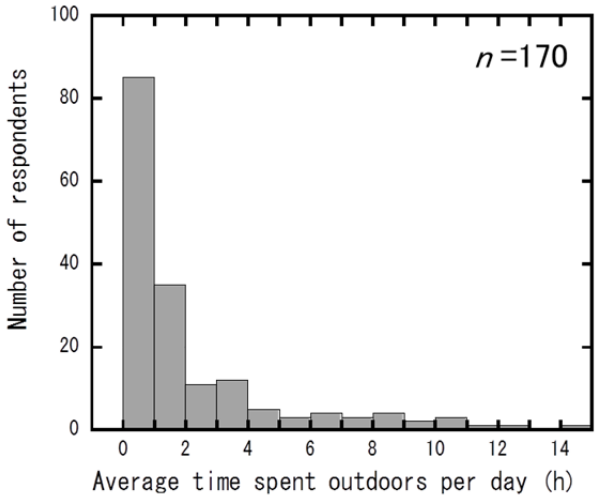


Figure 7. The distribution of average time spent outdoors (A_o) for respondents with four-month records (n=170).

3.2 *Relationship between average time spent outdoors and accumulated time of stay in Iitate Village*

The accumulated time of stay (outdoors, indoors and moving) in Iitate Village, T_t (h), was also analyzed in relation to average time spent outdoors per day. A distribution of T_t (h) for the 240 persons is given in figure 8 (left column in each accumulated time of stay grouping). As described in section 2.3, some evacuees came back to Iitate Village again before July 11, 2011 after temporarily evacuating to another municipality. In such cases, times for their second (or more) stay(s) in Iitate Village were also accumulated for T_t. If such persons are excluded from the 240 persons, the distribution of T_t that is shown in the right column in each time of stay grouping (n=152) is obtained. Among the 152 persons, 48 persons had behavior records of less than four months. Such persons might have spent more time within the first four months in Iitate Village than shown in figure 8, but that could not be confirmed from the obtained responses.

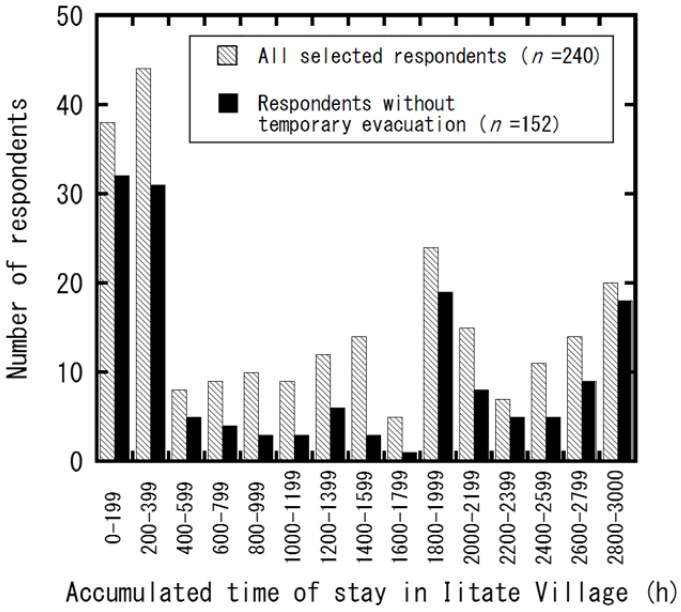


Figure 8. Distributions of the accumulated time of stay in Iitate Village (T_t) for the 240 persons and respondents without temporary evacuation.

However, the tendency for staying in the village among the evacuated residents indicated from figure 8 can be compared with another survey for evacuation patterns [13]. As described in the introduction section, on April 22, 2011, it was requested that residents and any other persons evacuate to other areas within roughly one month. The small peak for the 1,800-1,999 h accumulated time of stay grouping corresponded to the end of May, which was around the deadline to evacuate according to the government's instruction. The appearance of this peak was in accordance with the finding of another survey [13] which showed an increase in the number of evacuated persons at the end of May. The survey showed that around 65% of the residents evacuated by the middle of May, the ratio increased to around 80% by the beginning of June. Eighteen persons still remained in Iitate Village on July 11, the last date for the four-month records, according to the present analysis. This date corresponded to the accumulated time of stay grouping of 2,800-3,000 h.

The average time spent outdoors by age groups was also analyzed in relation to the accumulated time of stay in Iitate Village. The results are shown in figure 9. Generally, the age groups where average time spent outdoors was short (age groups of <10y, 10-19y, >80y), had short T_t. This indicated that these age groups generally evacuated earlier than other age groups. On the contrary, for age groups of 40-49y, 50-59y and 60-69y where the average time spent outdoors was long, T_t was longer compared with other age groups.

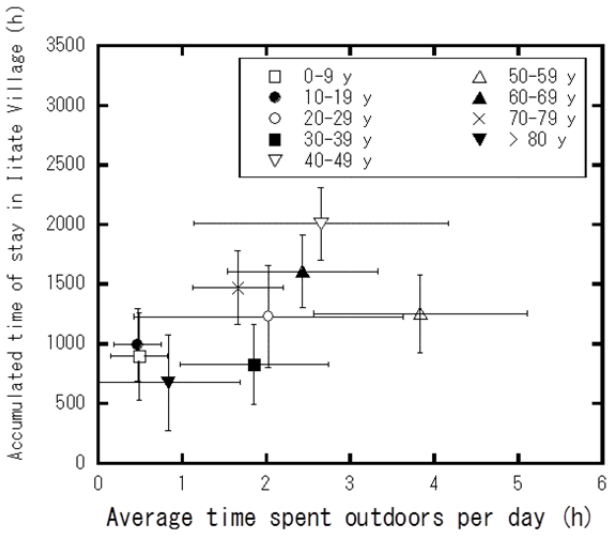


Figure 9. The average time spent outdoors per day by age groups, in relation to the accumulated time of stay in Iitate Village. Error bars show 95% confidence intervals.

3.3 *Relationship between average time spent outdoors and individual doses*

In the Basic Survey, individual external doses were estimated based on personal behavior records [9]. For the 170 persons with four-month behavior records, a distribution of individual doses is shown in figure 10. An average dose for the 170 persons was 4.1 mSv, which is similar to the average dose (4.0 mSv) for all respondents with four-month records (figure 2).

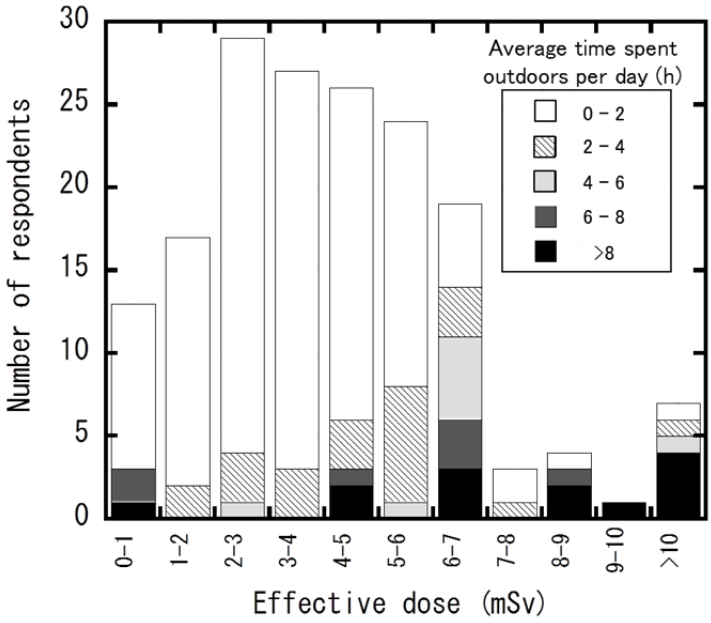


Figure 10. A distribution of individual doses for the 170 persons in relation to the average time spent outdoors per day.

As shown in figure 10, persons who had short average time spent outdoors per day (A_o < 2 h) tended to have a distribution at a lower dose range. On the contrary, persons who had larger values for the average time spent outdoors per day (A_o > 2 h) tended to have a distribution at a higher dose range. Three persons with A_o > 6 h in the dose range of 0-1 mSv seemed to be exceptions. This was because these persons voluntarily evacuated to another municipality before gamma ray dose rate in Iitate Village started to increase on March 15, although the time spent outdoors was longer during their short stay in Iitate Village. Among the 170 persons, 120 persons had A_o < 2 h. For the 120 persons, the average dose was 3.5 mSv (95% CI: 3.2-3.8). On the contrary, for 12 persons with A_o > 8 h, the average dose was 7.7 mSv (95% CI: 5.5-9.9). The difference could not be explained only by the difference in the average time spent outdoors. As discussed in section 3.5, dose reduction effect will be around 25%, when using A_o=2.08 h instead of 8 h. The difference between 3.5 and 7.7 mSv is beyond the level which can be explained by the difference in A_o. It may be because persons who had larger values for average time spent outdoors per day tended to have longer accumulated time of stay in Iitate Village, as shown in figure 9.

3.4 *Types of dwellings*

When estimating external dose from ambient dose rate outdoors and the daily time

budget, the dose reduction factor (R) is another influential factor (Eq. (2)). Among the 240 houses of respondents in the present study, 229 houses were wooden detached houses. The rest were categorized into ten apartments made of wooden and only one apartment made of concrete. Thus, the dose reduction factor for the respondents' own houses can be regarded as 0.4 and effects of A_o on external dose were estimated using Eq. (2) in the following sections.

3.5 *Effects of time spent outdoors on external dose*

Effects of time spent outdoors on dose estimation were considered by comparing the values of D corresponding to different values of t_o (Eq. 2). The results are shown in table 1. For example, if a person stayed indoors all day long (Case No. 3), D (the ratio of the external dose of Case No. 1 (staying outdoors all day long)) was calculated to be 0.4, which was equal to the reduction factor for wooden houses. Similarly, the ratio to Case No. 2 (outdoors, 8 h; indoors, 16 h) was calculated for different values based on the present analysis. When using the value of 0.99 h (the median value for the 170 persons) as t_o, the ratio was calculated to be 0.71. This indicates that the dose will be decreased by about 30% if 0.99 h is used instead of 8 h as t_o. In the same way, the dose will be decreased by about 25% if 2.08 h (arithmetic mean for the 170 persons) is used. Even considering the 95% CI of the arithmetic mean, the effects of dose reduction was almost the same (23-26% corresponding to the 95% CI of the arithmetic mean).

Table 1 Effects of time spent outdoors per day on external dose estimation.

Case No.	Explanation to the value shown in the right column	Time spent outdoors (t_o)	D (the dose ratio to Case No. 1)	The dose ratio to Case No. 2
1	Most conservative assumption	24	1	1.67
2	Common assumption	8	0.60	1
3	Minimum value in the present study	0	0.40	0.67
4	Median value in the present study	0.99	0.42	0.71
5	Arithmetic mean in the present study	2.08	0.45	0.75
6	Maximum value in the present study	14.5	0.76	1.27

Note: The values for t_o for the Case Nos. 3 to 6 were taken from values of A_o for the 170 persons with four-month records of activities and moves.

4. Discussion

For the 170 residents in Iitate Village selected from respondents to the Basic Survey, the average time spent outdoors was 2.08 h (arithmetic mean). It was much smaller than

the commonly used assumption of 8 h and also the most conservative assumption of 24 h. As described in the method section, the present analysis was faithfully based on the replies, but it was possible that some uncertainty in their replies existed due to faulty memories of their behaviors. However, the results based on their replies seem to be reasonable. For example, the difference in average time spent outdoors between age groups and gender (figures 5 and 6) can be reasonably explained. In addition, the maximum average time spent outdoors of 12.5 h (excluding commuters to Iitate Village as discussed below) is reasonable for an outdoor worker.

In analyzing the responses, it was found that some evacuees from Iitate Village lived in another municipality and commuted to Iitate Village where they worked outdoors, such as in farming and caring for livestock. In such cases, time spent outdoors per day tended to be estimated as larger than that of ordinary residents in Iitate Village. For example, if a person daily commuted to Iitate Village to work for a few hours per day only outdoors, A_o during the week was estimated to be 24 h (T_o/ T_t in Eq. (1) during the week is equal to 1), because the person was regarded as spending no time indoors in Iitate Village. These persons were not excluded from the analysis, therefore the A_0 shown here was likely to be overestimated. There were 26 such "commuters to Iitate Village" among the 170 persons who had the four-month records. If such persons were excluded from the analysis (n=144), the arithmetic mean became 1.80 h (95% CI: 1.36-2.23) with a range of 0 to 12.5 h (median, 0.92 h).

Considering the present results, the common assumption that people spend 8 h outdoors per day does not reflect the actual situations after the accident and using the assumption leads to overestimation of the external dose. When 2.08 h is used for the external dose estimation, the dose is decreased by about 25% compared with the dose estimated with the common assumption (table 1). In other words, using the common assumption leads to about a 30% overestimation of dose. In addition, using the most conservative assumption of being outdoors for 24 h a day results in a doubled dose compared with the estimation based on actual situations.

As an example, the average effective dose due to external radiation estimated by Imanaka et al. [16] was 7.0 mSv, using 8 h as the average time spent outdoors per day during the stay in Iitate Village. When 2.08 h is used instead as the average time spent outdoors per day, while keeping other parameters the same, their reported average dose (7.0 mSv) will be roughly decreased by around 25%, which results in a dose around 5.3 mSv. This is closer to 4.1 mSv, which is the average effective dose due to external radiation for the 170 respondents with four-month behavior records from Iitate Village, according to the present results. The difference between the average doses in the two

studies can be partially explained by the difference in time spent outdoors used in each study. For these two studies, apart from the average time spent outdoors, different approaches and parameters were used also.

One such difference was for the ambient dose rate. In the Basic Survey, this rate was estimated for each of the 2 km×2 km-mesh divisions covering all of Fukushima Prefecture based on environmental monitoring data, while Imanaka et al. [16] estimated it on the basis of a conversion from measured radionuclide concentrations in soil samples taken at dwelling places. A second difference was the period for dose estimation. It was from March 11 to July 11 in the Basic Survey, while it was from March 11 to July 31 in the study of Imanaka et al. A third difference was in dealing with the dose received outside of Iitate Village. The dose during stays in other municipalities within Fukushima Prefecture was considered and integrated for the four-month doses in the Basic Survey, while the dose received outside of Iitate Village was set to zero by Imanaka et al. Lastly, they interviewed 1,812 residents about each individual's whereabouts for each day after the accident. Unlike the behavior data of the Basic Survey (figure 3), however, the information on whereabouts (Iitate Village or other municipalities) was obtained in the unit of day (not hours). Then, they applied the given daily time budget (8h, outdoors and 16 h, indoors) and ambient dose rate at each resident's dwelling place with the given reduction factor of 0.4 for the people who stayed in Iitate Village on the day.

The dose estimates for residents in Iitate Village seem to be similar between the two studies, although there are differences of measured doses and the calculation process based on the estimate behind the external doses.

5. Conclusion

Time spent outdoors per day is an influential factor for external dose estimation. Responses to the questionnaire in the Basic Survey on moves and activities for the first four months after the FDNPP accident have been collected from residents in Fukushima Prefecture to estimate individual external doses during the period. In the present study, the responses were analyzed to estimate the average time spent outdoors per day for which Iitate Village was used as an example. The external doses to residents during the first four months were the highest for Iitate Village among all municipalities in Fukushima Prefecture. In the case of Iitate Village, the average time spent outdoors per day was 2.08 h (arithmetic mean, 95% CI: 1.64-2.51) for a total of 170 persons selected from Basic Survey respondents. It was much smaller than the commonly used value of 8 h. When 2.08 h was used for external dose estimation, the dose was decreased by about

25% compared with the dose estimated using a value of 8 h. The Japanese government's dose estimation method also has employed the assumption that people spend 8 h outdoors and 16 h indoors, and it will generally lead to overestimation of external dose, when it is estimated from ambient dose rate and daily time budget.

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