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A probabilistic approach to assess external doses to the public considering spatial variability of radioactive contamination and inter-population differences in behavior pattern

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ABSTRACT

Dose assessment is an important issue from the viewpoints of protecting people from radiation exposure and managing post-accident situations adequately. However, the radiation doses received by people cannot be determined with complete accuracy because of the uncertainties and the variability associated with any process of defining individual characteristics and in the dose assessment process itself. In this study, a dose assessment model was developed based on measurements and surveys of individual doses and relevant contributors (i.e., ambient dose rates and behavior patterns) in Fukushima city for four population groups: Fukushima City Office staff, Senior Citizens' Club, Contractors' Association, and Agricultural Cooperative. In addition, probabilistic assessments were performed for these population groups by considering the spatial variability of contamination and inter-population differences resulting from behavior patterns. As a result of comparison with the actual measurements, the assessment results for participants from the Fukushima City Office agreed with the measured values, thereby validating the model and the approach. Although the assessment results obtained for the Senior Citizens' Club and the Agricultural Cooperative differ partly from the measured values, by addressing further considerations in terms of dose reduction effects due to decontamination and the impact of additional exposure sources in agricultural fields, these results can be improved. By contrast, the measurements obtained for the participants from the Contractors' Association were not reproduced well in the present study. To assess the doses to this group, further investigations of association members' work activities and the related dose reduction effects are needed.

Keywords: Fukushima Daiichi Nuclear Power Plant accident, external dose, spatial variability, inter-population difference, probabilistic approach

1. INTRODUCTION

In the areas contaminated by the Fukushima Daiichi Nuclear Power Plant accident, many residents have been and continue to be exposed to radiation from the radionuclides spread by the Fukushima accident. To protect people from radiation exposure and manage post-accident situations adequately, dose assessment is an important issue[(1),(2)]. However, the doses actually experienced by people cannot be determined with complete accuracy because of the uncertainties and the variability in any process of defining individual characteristics and calculating radiation doses. These uncertainties arise from unavoidable limitations in the assessment. For example, measurements of concentration in environmental media have inherent limitations in terms of precision. Variability refers to real and identifiable heterogeneity or diversity in nature, and its sources can be classified into three categories: spatial, temporal, and inter-individual or inter-population[(3)]. In this study, we focus on the variability resulting from the spatial distribution of contaminants and the inter-population difference of behavioral patterns. These factors also give rise to a statistical spread in the distribution of doses among the people living in the areas contaminated by the Fukushima nuclear accident[(4),(5)].

To protect the people by taking into account these sources of uncertainty and variability, the International Commission on Radiological Protection (ICRP) recommended the concept of representative person to be used in making management decisions for contaminated areas[(6)]. This representative person, almost always a hypothetical construct, receives a dose representative of the more highly exposed individuals in the population. ICRP recommends the representative person should be defined in such a way that the probability is no more than 5% that an actual person drawn at random from the population will receive a greater dose.

Doses to the representative person can be assessed using several different approaches, including deterministic and probabilistic approaches. In many cases, assessors have performed deterministic calculations to derive mathematical expressions of exposures. This approach, however, has several limitations[(7),(8)]. For example, the degree and direction of conservatism may be masked completely by the reporting of a single number. Furthermore, a deterministic approach does nothing to guide decision-makers about whether to conduct additional research or about which of the available options should be applied to reduce exposure. This is because in deterministic approaches, outputs are often obtained by repeated use of the upper-bound point estimates, and information on the distributions of model parameters is not taken into account. In contrast, a probabilistic assessment can yield more complete characterization of dose distributions in the population[(7)–(9)] by considering the distributions of model parameters. Therefore, a probabilistic approach is better suited for sensitivity and uncertainty analysis than a deterministic approach. By using a probabilistic approach, assessors can get information on the degree of conservatism, and can provide insights that could further improve the precision of assessment.

However, when probabilistic approaches are applied to the assessment of radiation doses, variability in the contributing factors (such as exposure rates and behavior patterns) must be explained with statistical characteristics[(6)]. Moreover, to assess doses while realistically reflecting environmental trends and lifestyle habits, site-specific and population-specific data should be used. After the Fukushima accident, although several works on the assessment of the external doses to the population have been reported[(1),(2),(10)–(12)], most of these works were performed using a deterministic approach, and no study has adopted a probabilistic approach considering spatial and inter-population variability.

In the present work, we aim to develop a model for assessing radiation doses from external exposure in the areas contaminated by the Fukushima accident by using a probabilistic approach that considers spatial variability and inter-population differences in behavior patterns. The assessments are performed considering the concept of a representative person and from the viewpoint of protecting the people living in the areas contaminated by the Fukushima accident. To reflect the actual situation of the area contaminated by the Fukushima accident, we started development work based on our previous study[(4)], in which we provided results of the measurement of individual doses and analyzed the relationship between those results and the relevant contributors.

2. MATERIALS AND METHODS

2.1. Doses from external exposure and relevant contributors in Fukushima prefecture

In a previous study(4), we measured individual doses and the ambient equivalent dose rate inside and outside of houses, in addition to performing surveys on behavior patterns. These measurements and surveys were performed with the same individuals between February and April 2012. The participating individuals were asked every month whether they wished to continue their participation, and the number of participants decreased with time. The total participant numbers were 238, 145, and 116 in February, March and April, respectively. Because the number of participants was the highest in February, the assessment model was developed based on the data from this month. The data, which were obtained from the measurements and the surveys in February, were also used for in-sample tests. In addition, out-of-sample tests were performed by using the data obtained from the measurements and surveys in March and April.

2.1.1. Measurements of individual doses

Figure 1 shows the spatial distribution of the residences of the people who participated in the measurements and surveys. As shown in this figure, most of the participants lived in Fukushima city. Four population groups participated in the measurements and surveys: Fukushima City Office, Senior Citizens' Club of Fukushima city, Northern Fukushima affiliates of Contractors' Association, and Japan Agricultural Cooperative. In urban area and residential area of Fukushima city, ambient dose equivalent rates at the height of one meter above from the ground surface were measured by Fukushima prefecture(13) during the period between 21 and 24 February 2012. The sample size of this measurement was 127. On the basis of this measurement, the range of ambient dose equivalent rate was 0.02–2.2 μSv

h^{-1}, and geometric mean (GM) and geometric standard deviation (GSD) was 0.41μSv h^{-1} and 2.1, respectively.

Individual dose measurements were performed using personal dosimeters made by Hitachi-Aloka Medical, Ltd., PDM-122-SZ, which were calibrated appropriately to the dose equivalent at a depth of 10 mm in the tissue slab along the radius in the specified direction of 0°, as recommended by the International Commission on Radiation Units and Measurements. In this study, the term "individual dose" refers to the readings obtained using the personal dosimeters. Based on the report of the Working Group on the Concept of Doses, under the Division of Radiation Science and Technology of the Atomic Energy Society of Japan(14), if a personal dosimeter calibrated as mentioned above was used for measurements in the areas contaminated by ^{134}Cs and ^{137}Cs, the obtained measurement should be considered equivalent to the effective dose in rotation geometry (ROT). Furthermore, they pointed out that the irradiation geometry in the contaminated areas can be approximated with ROT(14). Therefore, we regarded the individual dose measured with the personal dosimeters in contaminated areas as equivalent to the effective dose which was experienced by the people in those areas. In addition, the measured values of individual doses vary depending on dosimeter position and direction of incidence of photons. Zankl(15) reported variations in the measured values with changes in the position of the dosimeter within the body trunk. These variations can be up to several percent in ROT and are the largest in posteroanterior (PA) geometries, with a maximum of approximately 30%.

ICRP has recommended that the necessary degree of homogeneity in the data used for assessments should depend on the ratio of the mean dose in the population group to the relevant dose limit or constraint(6). If that ratio is less than about one-tenth, the group should be regarded as homogeneous, provided that the ratio between the maximum and the minimum values is no more than 10. If the ratio of mean dose to relevant dose limit is higher than one-tenth, then to achieve homogeneity, the maximum should be no more than three times the minimum value. In the present study, the annual individual doses to the populations were estimated to be several mSv. The ratio of the estimated GM of individual doses, which was obtained from the data of entire population groups, to the dose limit (i.e., 1 mSv per year)[16] is greater than one-tenth. Thus, the ratio between the maximum and the minimum values should be less than 3. Here, we used GMs for evaluating the ratio because the individual doses were distributed in lognormal form as mentioned in our previous study[4].

Table I shows the statistical characteristics of the measured individual doses for each population group. The measured individual doses for entire population groups were in the range of 60–317 μSv per month, 64–414 μSv per month and 71–428 μSv per month in February, March and April 2012. Thus, the ratios between the maximum and the minimum values are 5.3, 6.5, and 6.0, respectively, so the data cannot reasonably be assumed to be homogeneous. By contrast, if the measured individual doses are classified in terms of population groups, the ratio can be reduced to approximately 3 in case of the participants from the Fukushima City Office, the Senior Citizens' Club, and the Contractors' Association. Our previous study[4], in which we statistically analyzed individual doses measured from February to April 2012, suggested that the homogeneity requirement could be satisfied for these three population groups. However, even after the data were classified with respect to participant group, clear non-homogeneity was found in individual doses received by participants in the Agricultural Cooperative population. Although the following assessments assume the classification of population groups, this lack of homogeneity in one of the groups should be noted.

2.1.2. Measurements of ambient dose equivalent rates

Measurements of ambient dose equivalent rates were performed in early February 2012. The number of participants was 238 (215 households) for outdoor measurements and 207 (184 households) for indoor measurements. The measurements were performed using energy-compensated NaI(Tl) scintillation survey meters (Hitachi-Aloka Medical, Ltd., TCS-171B). The ambient dose equivalent rates outside houses were measured at 1.2 m from the front door. This representative location of outdoor measurements was determined to be practicable and acceptable to the public. To determine locations for indoor measurements, the participants were asked where in the house they spend the most time. The measurement height was one meter above the outdoor ground surface and one meter above the indoor floor level. In addition, snow accumulation was observed in January and February 2012 in Fukushima prefecture. It should be noted that the reduction effects of ambient equivalent dose rate due to this snow accumulation were reported(17). The measured ambient dose rate was in the rage of 0.07–0.55 μ Sv h^{-1} inside houses and 0.07–1.76 μSv h^{-1} outside houses. The GM and GSD of those measured outside houses was 0.35μSv h^{-1} and 1.70, respectively(4). This result does not contradict the results measured by Fukushima prefecture(13) described in 2.1.1.

In this study, we convert the measured ambient dose equivalent rate, $H^{*}(10)$, into the absorbed dose rate in air, D_a. We used 1.21 as the value of the conversion factor $H^{*}(10)/D_a$ for the photon energy of 0.6 MeV, based on ICRP's recommendation(18). Because the photon energy contributing to external exposure is governed by the energy from ^{134}Cs and ^{137}Cs, the effective energy was estimated to be 0.68 MeV as of February 2012 based on the composition data in the UNSCEAR report(2). Here, we assumed that the loss of energy due to bremsstrahlung is negligible. Thus, the air kerma, K_a, is equivalent to the absorbed dose in air, D_a.

Figure 2 shows the correlation between absorbed dose rates in air as measured inside and outside houses. This correlation reflects the characteristics of the participants' houses, most of which are composed of wooden materials. The adjusted R-squared statistic for this correlation is 0.45, which means that there was no clear correlation. However, based on the results of the F-test, the ambient dose rates measured inside the houses are explained well by the dose rates measured outside(4). We used this correlation to develop a dose assessment model as described in 2.2.

Table II shows the statistics of the measured absorbed dose rates for each population group. According to our previous study(4), the ambient dose equivalent rate was distributed in lognormal form, and thus the same distribution was assumed for the dose absorbed in air. In addition, the arithmetic mean (AM) of the logarithmic value of the absorbed dose rates for the participants from the Fukushima City Office, the Contractors' Association and the

Agricultural Cooperatives had no significant differences with the results of t-tests. However, the AM of the logarithmic value of the absorbed dose rates for the Senior Citizens' Club was higher than those for the other three groups with a significance level of 5%. This is because the participants from the Senior Citizens' Club were selected from areas with relatively higher levels of contamination in Fukushima city based on a request by the Senior Citizens' Club itself. Moreover, these areas were designated as priority areas for decontamination in Fukushima city[19], and decontamination efforts were started in February 2012.

2.1.3. Survey on behavior patterns

To obtain information on behavior patterns, surveys were performed regarding the time that people spent inside and outside their houses, at their workplace, and in other locations. Participants tracked the amount of time spent in each place every day, and these data were collected by mail on a monthly basis. **Table III** shows the statistics of the time spent outdoors per day by each population group, as obtained from our surveys in February, March and April, 2012[4]. As shown in this table, the population groups can be classified into two categories. The first category includes people who spent the largest amount of time inside houses or workplaces, including the participants from the Fukushima City Office and the Senior Citizens' Club. The second category contains people who spent more time outdoors, such as those from the Contractors' Association and the Agricultural Cooperative.

Two clear differences were found between the two categories in terms of time spent outdoors and its distribution. First, the time spent outdoors for the second category, which was in the range of 5–8 hours per day, was clearly longer than that for the first category, which was 1–2 hours. Second, the distributions of time spent outdoors of the first category and the second category were lognormal and normal, respectively. In general, the time spent outdoors by the people who work indoors is distributed in a positively skewed shape such as lognormal distribution[20]. The time spent outdoors by the participants from the Fukushima City Office and the Senior Citizens' Club also showed the same trend as that reported in our previous study[4]. For these participants, normality was examined for the logarithmic values of time spent outdoors because p-value of the normality-test for the Fukushima City Office and the Senior Citizens' Club is 0.302 and 0.160, respectively. In contrast, for the Contractors' Association and the Agricultural Cooperatives, p-value of the normality-test for the logarithmic value of time spent outdoors was 4.46×10^{-11} and 2.02×10^{-2}, respectively. These results for the Contractors' Association and the Agricultural Cooperatives indicated that normality is rejected. However, for the participants from the Contractors' Association and the Agricultural Cooperatives, if we used the surveyed results directly, which means non-logarithmic value, p-value for the normality test was 0.848 and 0.0771, respectively. This result indicates that normality is not rejected. Therefore, normal distribution is assumed for the time spent outdoors for these groups. The participants from the Contractors' Association and the Agricultural Cooperative spend their working time outdoors routinely. Therefore, time spent outdoors for these participants should be determined by the working time, and it could be distributed in the normal form, with the average time according to the working time.

2.2. Assessment model for external exposures

In a previous study[4], the authors conducted a multi-regression analysis to explore a significant relationship between individual doses and relevant contributors based on the measurements and surveys performed in February 2012. The results of that study clearly indicated that the ambient dose equivalent rates measured outside houses and the total amount of time spent outdoors per day had a significant relationship with the individual doses, and they could describe most differences in individual doses quite well. Thus, we decided to develop an assessment model for the effective dose from external exposure, E_j^{gd}, based on the air dose rate measured outside houses, $D_{a,out}$, and the total time spent outdoors per day, t_{out}:

$$E_j^{gd} = \int \left\{ k_E \cdot \left(f_l(t) \cdot D_{a,out,j} \cdot \frac{t_{out,j}}{24} + (0.26 \cdot D_{a,out,j} + 0.10) \cdot \left(\frac{24 - t_{out,j}}{24} \right) \right) \right\} dt, \quad (1)$$

where $f_l(t)$ is the location factor for urban locations of type l at time t after the contamination occurred, k_E is a factor for conversion of the absorbed dose in air into the effective dose, and j denotes the population group (i.e., one of the four participating organizations). k_E was set to 0.81 for the photon energy of 0.6 MeV[18]. The absorbed dose in air as measured inside houses was projected by the relationship between the indoor and outdoor measurements as shown in **Fig.2**.

The index l for location type distinguished between virgin land, dirt surfaces, and asphalt, which were classified according to the characteristics of the ground surface[21],[22]. The location factors are represented as a function of the time elapsed after the contamination, as follows:

$$f_l(t) = a_{l,1} \cdot exp\left(-\frac{ln\,2}{T_l} \cdot t\right) + a_{l,2}, \quad (2)$$

where $a_{l,1}$, $a_{l,2}$, and T_l are fitting parameters for the location factors of cesium. The values of these parameters are listed in **Table IV**; they were determined from the data obtained after the Chernobyl nuclear accident[22]. In the present study, calculations were performed for the participants of our measurements and surveys by assuming that they live in urban areas, in view of the environment of Fukushima city. Thus, it was assumed that the participants from the Fukushima City Office and the Senior Citizens' Club spend all day in areas paved with asphalt. In addition, measurements of the ambient dose equivalent rates can also be regarded as data from surfaces paved with asphalt. However, we assumed that outdoor workers (i.e., the participants from the Contractors' Association and the Agricultural Cooperative) spend their working hours in areas classified as dirt surfaces. The ratio of location factor between dirt surfaces and asphalt was used for correcting the doses in their working place. The values of 1.57, 1.62 and 1.67 were used for February, March and April 2012, respectively.

3. RESULTS AND DISCUSSION

3.1. In-sample test

At first, in-sample tests were performed to compare individual doses between the assessed values and the measured values. The assessments were performed by using the developed model given by Eq. (1), based on the results of the measurements and surveys in February 2012. The sets of $D_{a,out}$ and t_{out} were generated on the basis of the statistical characteristics described in **Table II** and **Table III** by using a Monte Carlo analysis code called GSALab[23], which was developed by the Japan Atomic Energy Agency. The calculations of individual doses per day were performed for 10,000 sets of sample values by Eq. (1). Relative errors in the assessments were less than 5%.

The assessment results are shown in **Fig.3**. The measured values shown in this figure are the averages of individual doses per day, which were calculated from the data in February 2012 for each participant. The assessment results of the participants from the Fukushima City Office and the Agricultural Cooperative were in good agreement with the measured values and met the aims of our dose assessment in two regards. First, the 95th percentile of assessed values was larger than that of the measured values, so the assessments could be validated with regard to conservativeness. This means that the assessments can provide the doses for the representative person without underestimation of doses. Second, the differences in the AMs between the measured values and the assessed values for the Fukushima City Office and the Agricultural Cooperative populations were 2% and 1%, respectively. These differences are within the measurement error due to variation of dosimeter position and direction of photon incidence.

However, in case of the participants from these population groups, we can see that overall, the assessed doses tend to be smaller than the measured values. This tendency was particularly clear in case of the participants from the Agricultural Cooperative, who were exposed to relatively higher doses. The participants from the Agricultural Cooperative work as farmers in their daily lives, growing various agricultural products such as fruits, rice, vegetables, flowers, and livestock. According to an analysis in our previous study[4], most of the participants with the highest exposure are engaged in fruit production. In addition, Naito *et al*.[24] shows that a higher individual dose was observed during daytime and outside working hours for farmer with increasing the ambient dose equivalent rate in their working places. Naito *et al*.[5] also pointed out when farmers spend long time in their working place with relatively high ambient doses, the contribution of the doses received in their working place are more than 70% of the total daily exposures. Therefore, to improve the precision of our assessment, we must explore the contribution of agricultural activity to the total individual dose per day taking into account relationship among the individual dose, behavioral patterns and ambient dose equivalent rate in agricultural field.

In contrast to the results of the participants from the Fukushima City Office and the Agricultural Cooperative, those of the Senior Citizens' Club and the Contractors' Association did not agree well with the measured values. The doses for the participants from the Senior Citizens' Club were based on the assumption that these participants spend most of their time outdoor on paved surfaces (i.e., asphalt) in their outdoor activity. However, from the information obtained by interviewing participants about their behavior patterns, it was learned that they spent their time outdoor on dirt surfaces, for instance, performing agricultural work. To reflect this behavior, in the assessments, we used the location factor for dirt surfaces rather than that for asphalt in case of the participants from the Senior Citizens' Club who reported spending time outdoors. The modified results for the participants from the Senior Citizens' Club are shown in **Fig.3** as a dashed line. With this adjustment, the 95th percentile of the assessed values became larger than that of the measured values, and the difference in the AMs between the measured values and the assessed values decreased to less than 1%. Consequently, the assessment results were improved by this adjustment, and they now fulfill the two validity considerations mentioned above. However, even after this modification, the assessed values still tend to be lower than the corresponding measured values. To address this tendency, as with the participants from the Agricultural Cooperative, it is necessary to consider the contribution of outside working hours to the total individual dose per day

The results of the participants from the Contractors' Association displayed significant statistical differences between the measured values and the assessed values. In particular, a characteristic difference was observed among the highly exposed participants in this group. The members of this group with higher exposure levels tended to spend greater amounts of time outside of their houses and workplaces. However, the measured values of these participants were not as high as those estimated by our model. In fact, the measured individual doses had no significant correlation with time spent outdoors, based on the results of multi-regression analysis[(4)]. The difference between the measured values and the assessed values, shown in **Fig.3**, and the results of our multi-regression analysis imply that the doses experienced by contractors at their workplaces could be influenced by dose reduction effects. In our interviews of participants from the Contractors' Association, we identified a few activities that could be associated with dose reduction effects. For example, operation of heavy equipment and working in high places can provide dose reduction effects due to equipment or due to greater distance from ground surfaces contaminated by radionuclides. Therefore, to improve the applicability of the dose assessment model to the participants from the Contractors' Association, further investigation of their work activities and the resulting dose reduction effects is needed.

3.2. Out-of-sample test

In sections 2.2 and 3.1, the dose assessment model was developed and its validity was confirmed by performing an in-sample test based on the results of the measurements and surveys from February, 2012. In this section, to confirm validity of the developed model, out-of-sample tests were performed based on the measurements and surveys in March and April 2012. The $D_{a,out}$ statistics used in the in-sample test were used in the out-of-sample test as well. The t_{out} statistics used in the out-of-sample test were obtained from the results of the surveys in March and April 2012, as given in **Table III**. In the same manner as in the in-sample test, 10,000 sets of $D_{a,out}$ and t_{out} were generated, and the assessment results are shown in **Fig.4**.

The assessment results of the participants from the Fukushima City Office were in good agreement with the measurements recorded in March and April. Both individual doses and time spent outdoors for the participants from the Fukushima City Office were not significantly different during the period between February and April 2012. The differences in AMs between the measured values and the values assessed in March and April were 2% and 4%, respectively. In addition, the 95th percentile of the values assessed in March was larger than that of the measured values. Although we can see that the assessed values tend to be slightly lower than the measured ones in April, this could be attributed to the dose reduction effects due to the accumulation of snow, as mentioned in 2.1.2. Therefore, if the air absorbed dose rate measured without the effect of snow accumulation were used for the assessment, the accuracy would improve. Thus, we validated the model and the probabilistic approach developed herein in case of the participants from the Fukushima City Office.

In case of the participants from the Senior Citizens' Club, the assessment results, which were corrected using the location factor for dirt surfaces, tended to be lower than the measured values. In particular, differences between the assessed values and the measured values in terms of individual doses increased for the more highly exposed individuals in the population. This feature was apparent more clearly in April. As described in 2.1.2, the participants from the Senior Citizens' Club lived in areas with relatively higher contamination in Fukushima city, and decontamination efforts in those areas were started in February 2012. In the decontamination efforts, the first priority was accorded to the people for which radiation dose rates in their houses are higher than those of others in the area[(19)]. Thus, the dose reduction effects should be observed first in the more highly exposed individuals, and then in the other group members. Since the decontamination efforts progressed gradually after February and the houses of increasing number of participants' were decontaminated with time, the differences in individual doses between the measured values and the assessed values were more pronounced in April.

In case of the participants from the Contractors' Association and the Agricultural Cooperative, the same tendencies were observed as those in the in-sample tests. This means that the results obtained for the Contractors' Association differed significantly in terms of distribution forms and statistics, and the results for the Agricultural Cooperative tended to be lower than the corresponding measured values. In particular, as mentioned in 3.1, for the Agricultural Cooperative, the differences in individual doses between the assessed values and the measured values may have been caused by exposure to other radiation sources in addition to contaminated ground surfaces in the course of agricultural works. In fact, the differences in individual doses between the assessed values and the measured values in April were more pronounced than those in March. This is because that the time spent outdoors by the participants form the Agricultural Cooperative increased with the transition from agricultural off-season to farming season. Therefore, the contribution of exposure at work place to the individual doses increased in April. As a result, the differences between the assessed values and the measured values increased as well. As mentioned in 3.1, to improve these points, further studies considering the dose reduction effects due to work activities and contributions from outside working will be required. Moreover, in case of the Agricultural Cooperative, as mentioned in 2.1.1, non-homogeneity was observed among individual doses. According to a previous study[(4)], the individuals engaged in producing rice and fruits were exposed to higher doses than individuals engaged in other farming activity. Therefore, reclassification in terms of types of agricultural producers is one way to improve the assessment results.

3.3. Limitations of our assessment and implications for future work

The authors expect that the developed probabilistic approach can provide valuable information for making decisions on whether to implement protective actions and/or to return to the contaminated areas. For example, if data on the air absorbed dose rate in the evacuation zones are available, the radiation doses to which people will be exposed to after they return to the evacuation zone can be assessed in advance. Especially, we found that individual doses for the participants from the Fukushima City Office could be assessed by using the present probabilistic approach and the developed model. However, the assessments and calculations herein have some important limitations and assumptions that will require clarification through additional trials.

First, in this study, a probabilistic approach was developed and validated against actual measurements in Fukushima city by considering the spatial variability of contamination and the inter-population variability of behavioral patterns. In particular, for spatial variability, although the GSDs used in our assessments were in the range of 1.53–1.76, these values were obtained from limited measurements in residential areas in Fukushima city. As described in a previous study[25], the GSDs for contamination level in Fukushima prefecture have larger variability than those used in this study. For example, the differences in contamination levels were caused by differences in the type of land use and the location of a given municipality. Therefore, to make an assessment with satisfactory accuracy, the assessors should collect data by taking into account these differences based on the target of their assessment. These effort include revision of the location factor. In our model, the location factor was obtained from environmental data on the Chernobyl nuclear accident. If sufficient data and insights on the Fukushima accident become available, modifications based on this additional information may be needed.

Second, whether the probabilistic approach and the dose assessment model developed in this study can be generalized depend on the used data (i.e. behavioral pattern, and the absorbed dose rates in air as measured inside and outside houses). The statistics of behavioral patterns were obtained from the four population groups in Fukushima prefecture. If behavioral patterns similar to those groups can be assumed for others who have similar occupations, it is possible to assess the doses probabilistically using statistics obtained in this study. On the other hand, the dose assessment model was developed based on the relationship between the dose rate measured inside and those measured outside. As well known, this relationship depends on type of house (e.g. size, wood/concrete)[26],[27], surrounding environmental condition (e.g. building coverage rate, roughness of surface)[28], and time after deposition onto the surfaces (e.g. migration into the soil[29], time-dependence of effective strength of different urban surfaces[30]).

Therefore, if assessors use the dose assessment model developed in this study, they have to modify the model taking into account these factors affecting the relationship between the dose rate measured inside and those measured outside.

Third, in the present study, dose assessments were performed by using the doses received per day or per month. A previous study indicated that individual doses in the Agricultural Cooperative population increase due to the transition from agricultural off-season to farming season[4]. Since the data in the present study were obtained in the agricultural off-season, they cannot be used for assessing the doses in the farming season. Moreover, it is known that distribution of the estimated average daily behavior pattern over a short period is more widely spread than the actual behavior patterns over a long period; for assessing the doses received from longer-term exposure, data on behavior patterns from long-term observations will be needed to reduce the influences of seasonal and temporal variability[31],[32].

4. CONCLUSION

A dose assessment model was developed based on the measurements of individual doses and radiation dose rates, and surveys on behavior patterns in Fukushima prefecture. Using the developed model, dose assessments were made using by a probabilistic approach. The assessments were made for four population groups: the Fukushima City Office staff, Senior Citizens' Club, Contractors' Association, and Agricultural Cooperative. To confirm validity of the model and the approach, an in-sample test and an out-of-sample test were performed. The results of the in-sample test for the participants from the Fukushima City Office, the Senior Citizens' Club, and the Agricultural Cooperative were in good agreement with the measured values. In addition, results of the out-of-sample test for the participants from the Fukushima City Office agreed with the measurements. As a result, we found that individual doses for the participants from the Fukushima City Office could be assessed by using the present probabilistic approach and the developed model. By contrast, the assessment results obtained for the Senior Citizens' Club and the Agricultural Cooperative were not validated by the out-of-sample test. However, these results can be improved if the dose reduction effects due to decontamination and the contribution of outside working in agricultural fields are considered. In particular, seasonal changes in the time spent outdoors by the participants from the Agricultural Cooperative must be taken into account. In contrast to the results for the other three groups, the doses for the participants from the Contractors' Association were not reproduced well in this study. For this group, additional information is needed to clarify their work activities and to develop a model that considers changes in exposure rate associated with those activities.

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Figure captions

Fig. 1 Spatial distribution of participants in measurements and surveys as of February 2012.

Fig. 2 Relationship between absorbed dose rate in air as measured inside and outside houses.

Fig. 3 Results of in-sample test for each population group.

Fig. 4 Results of out-of-sample test for each population group.

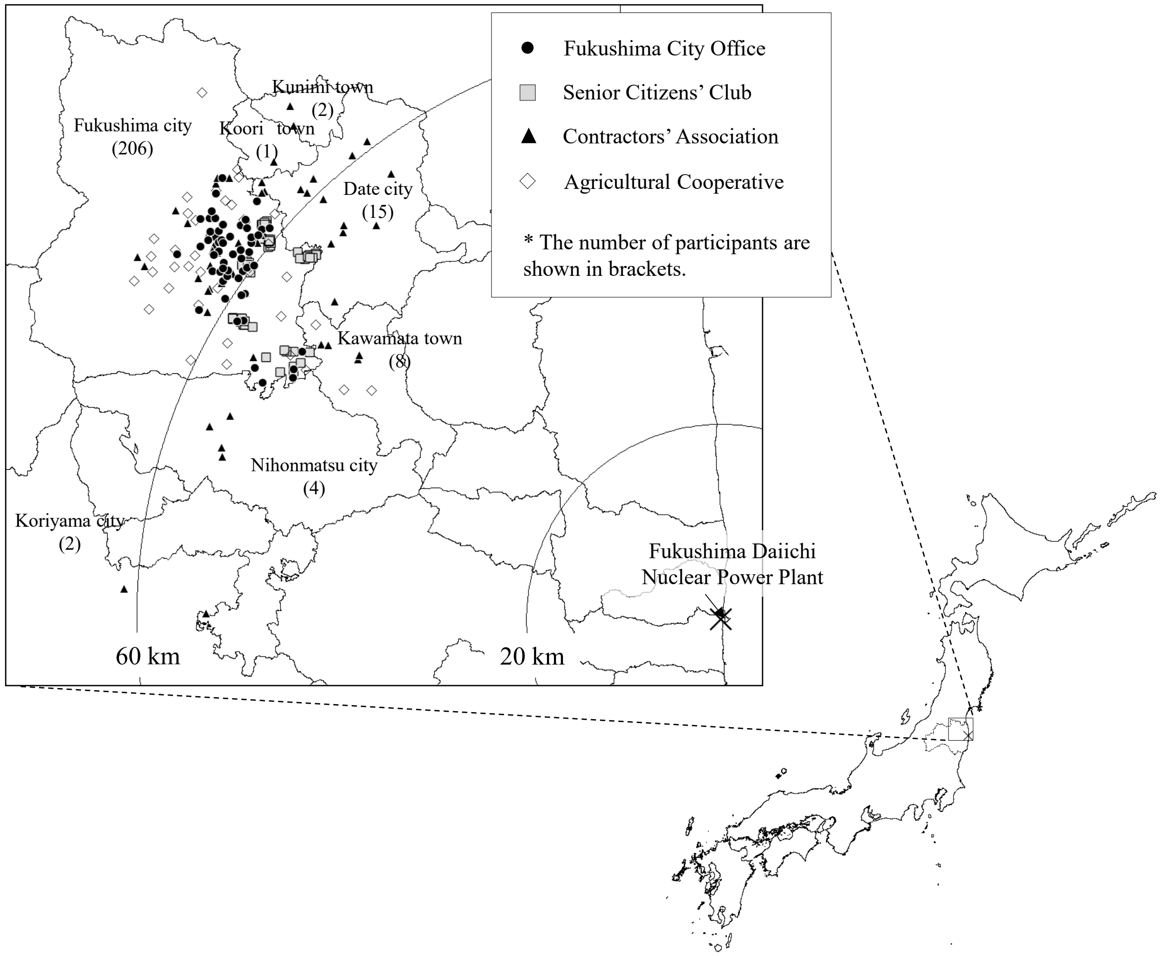
Table captions

Table I Statistics of measurement results of individual doses for each population group.

Table II Statistics of absorbed dose rate in air measured outside houses for each population group.

Table III Statistics of time spent outdoors by each population group.

Table IV Parameters for location factors of cesium in urban environment(21)



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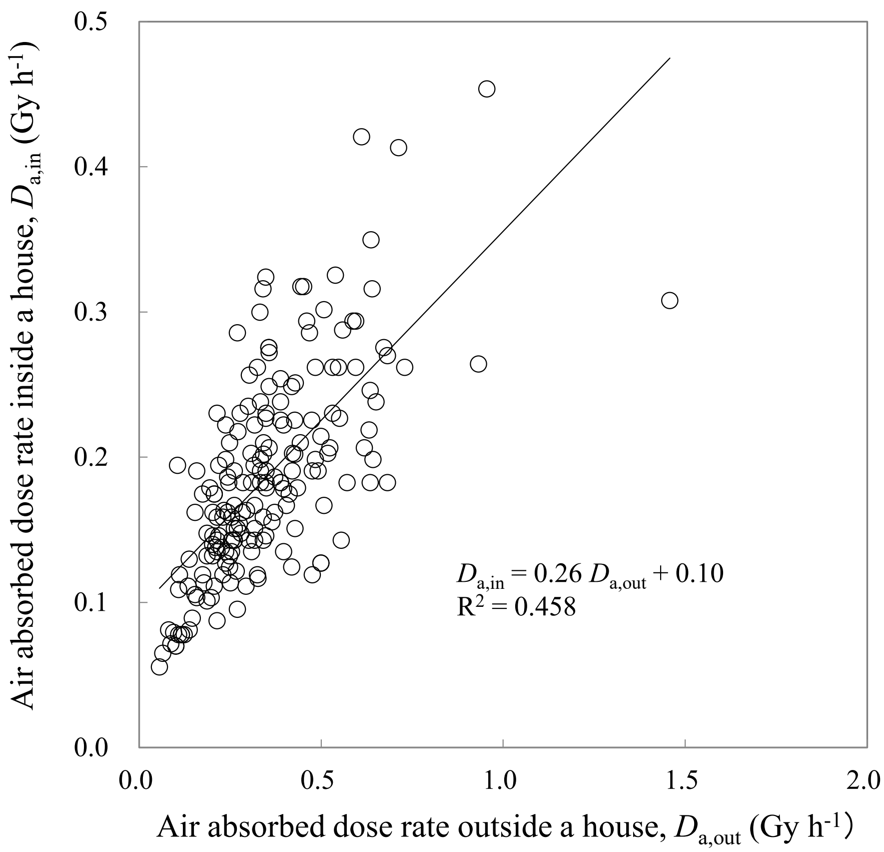

Fig.2 Relationship between absorbed dose rate in air as measured inside and outside houses.

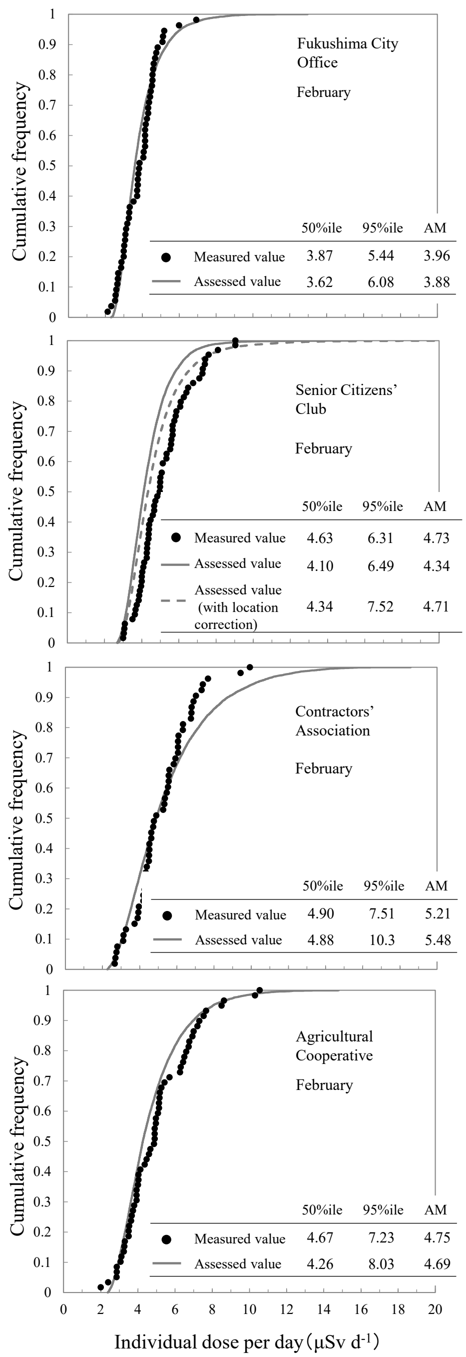

Fig.3 Results of in-sample test for each population group.

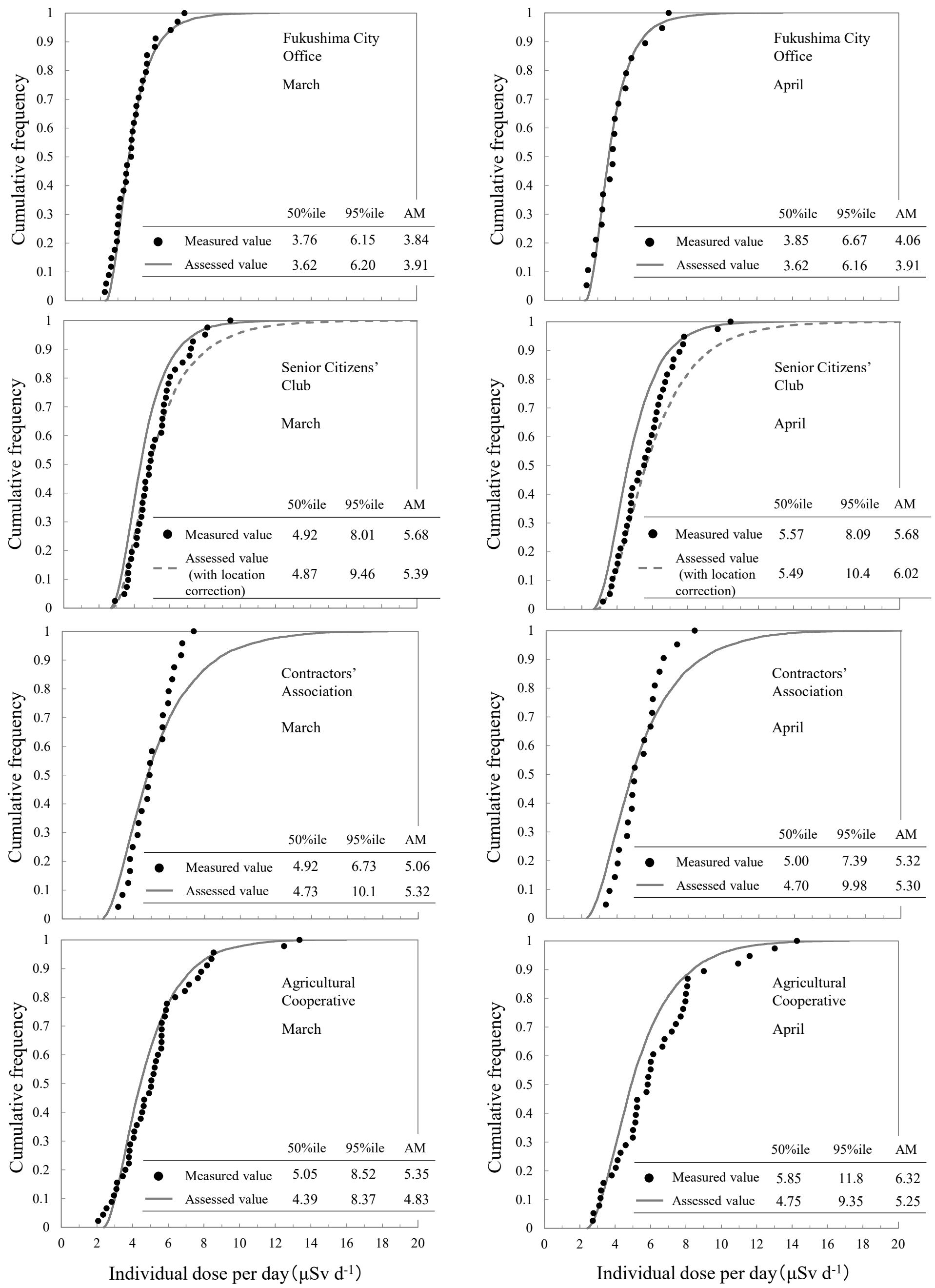

Fig.4 Results of out-of-sample test for each population group.

Table I Statistics of measurement results of individual doses for each population group.

		Individual dose per month (μSv)		
		Feb.	Mar.	Apr.
Fukushima City Office	Sample size	60	35	19
	GM	112	115	117
	Max.	208	211	210
	Min.	64	70	71
	Max/Min	3.3	3.0	3.0
Senior Citizens' Club	Sample size	65	41	38
	GM	150	156	164
	Max.	271	293	313
	Min.	90	90	96
	Max/Min	3.0	3.2	3.3
Contractors' Association	Sample size	53	24	21
	GM	150	153	155
	Max.	298	229	251
	Min.	80	97	101
	Max/Min	3.7	2.4	2.5
Agricultural Cooperative	Sample size	60	45	38
	GM	143	153	174
	Max.	317	414	428
	Min.	60	64	82
	Max/Min	5.3	6.5	5.2

Table II Statistics of absorbed dose rate in air measured outside houses for each population group.

	Absorbed dose rate in air		
	Distribution[1]	GM ($\mu Sv\ h^{-1}$)	GSD
Fukushima City Office	LN	0.30	1.70
Senior Citizens' Club	LN	0.38	1.53
Contractors' Association	LN	0.25	1.76
Agricultural Cooperative	LN	0.26	1.67

[1] LN means lognormal distribution.

Table III Statistics of time spent outdoors by each population group.

	Time spent outdoors per day				
	Distribution[(1)]	Stats[(2)]	Feb.	Mar.	Apr.
Fukushima City Office	LN	GM	0.41	0.58	0.82
		GSD	3.72	3.48	2.65
Senior Citizens' Club	LN	GM	0.96	1.28	1.68
		GSD	3.64	4.28	2.19
Contractors' Association	N	AM	7.62	7.56	7.46
		SD	2.82	2.61	2.40
Agricultural Cooperative	N	AM	5.18	6.12	7.89
		SD	3.34	3.33	2.87

(1) LN and N means lognormal and normal distribution, respectively. (2) Units of AM, GM and SD are "hour". GSD is a dimensionless quantity.

Table IV Parameters for location factors of cesium in urban environment[22].

Type of location	$a_{l,1}$	$a_{l,2}$	T_l (y)
Virgin land	0.32	0.68	1.4
Dirt surface	0.50	0.25	2.2
Asphalt	0.56	0.12	0.9