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Author(s)	Ishikawa, Tetsuo; Yasumura, Seiji; Akahane, Keiichi; Yonai, Shunsuke; Ohtsuru, Akira; Sakai, Akira; Ohira, Tetsuya; Kamiya, Kenji
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Fukushima Medical University

Age dependence of individual external doses in an early stage after the Fukushima nuclear accident

Tetsuo Ishikawa[1), *], Seiji Yasumura[1)], Keiichi Akahane[2)], Shunsuke Yonai[2)], Akira Ohtsuru[1)], Akira Sakai[1)], Tetsuya Ohira[1)], Kenji Kamiya[1, 3)]

[1] Radiation Medical Science Center for the Fukushima Health Management Survey, Fukushima Medical University, Hikarigaoka 1, Fukushima City, 960-1295 Japan
[2] National Institutes for Quantum and Radiological Science and Technology, 4-9-1 Anagawa, Inage-ku, Chiba City, 263-8555 Japan
[3] Hiroshima University, 1-2-3 Kasumi, Minami-ku, Hiroshima City, 734-8551 Japan

*Corresponding author:
Tel:+81-24-547-1924
E-mail: isikawat@fmu.ac.jp
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Age dependence of individual external doses in an early stage after the Fukushima nuclear accident

Tetsuo Ishikawa, Seiji Yasumura, Keiichi Akahane, Shunsuke Yonai, Akira Ohtsuru, Akira Sakai, Tetsuya Ohira, Kenji Kamiya

Abstract

Individual external doses for the first four months after the Fukushima accident have been estimated by the "Basic Survey" of the Fukushima Health Management Survey. On the other hand, the UNSCEAR 2013 report presented the first-year effective dose due to external radiation for each municipality in non-evacuated areas of Fukushima Prefecture. In this study, the doses estimated by the Basic Survey were averaged for each of three age groups (infants, 0-5 y; children, 6-15 y; and adults, >16y), in accordance with the categories adopted by the UNSCEAR report. The average dose ratios (infants/adults and children/adults) obtained from the Basic Survey were 1.08 and 1.06 for non-evacuated areas, respectively. These were smaller than the estimation by the UNSCEAR report (1.7 and 1.4, respectively). Three factors (body size factor, location factor, and occupancy factor) were discussed and the location and occupancy factors were likely to be reasons for the difference.

INTRODUCTION

Large amounts of radionuclides were released into the environment due to the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident in March 2011. Both internal and external exposures to the public occurred [(1)]. These doses can differ from person to person even in the same area; they vary by such characteristics as age, behavior (or evacuation) pattern after the accident, food intake and so on. In the case of the external dose integrated for a period, the difference can be caused by: (1) a location factor depending on ambient doses for sites (indoors/outdoors) where residents spent time after the accident; (2) an occupancy factor depending on daily time budget for the sites; and (3) a body size factor depending on extent of absorption and scattering of gamma rays in bodies of different sizes [(2-4)]. The location factor is a similar concept to “shielding factor” or “dose reduction factor” [(5)]. However, the term “location factor” is used here, in accordance with the UNSCEAR 2013 report. The first two factors mainly depend on gamma dose rates at the sites (associated with types of buildings (indoors) or ground conditions (outdoors)) and daily life patterns. The daily life patterns can be characterized by age and occupation. The last one depends almost only on age, assuming that the average body size depends almost exclusively on age, especially for children.

The UNSCEAR 2013 report [(1)] summarized doses received by the public in Fukushima Prefecture as well as other areas. For the estimation of doses, the UNSCEAR Committee considered three main age groups at the time of the accident: adults, children and infants. Twenty-year-old adults were chosen to represent all adults, 10-year-old children to represent all children older than 5 years old, and one-year-old infants to represent all infants younger than five years old. The UNSCEAR 2013 report presented the first-year effective dose due to external radiation from deposited radionuclides for each municipality in non-evacuated areas of Fukushima Prefecture. For example, the district-average effective dose for Fukushima City was estimated to be 3.02 mSv for adults, while it was 5.03 mSv for one-year-old infants and 4.25 mSv for 10-year-old children. Here, the contribution from external exposure due to radioactivity in air (the radioactive plume released) was estimated to be zero and external dose only from deposited radionuclides was considered. The first-year dose for 1-year-old infants was around 1.7 times larger than that for adults. For 10-year-old children, it was around 1.4 times larger. The ratios were similar for all municipalities in non-evacuated areas of Fukushima Prefecture.

On the other hand, Fukushima Prefecture and Fukushima Medical University have conducted the "Basic Survey", which estimates individual external doses for the first four months after the accident [6, 7]. Individual dose estimation by the Basic Survey is based on behavior records obtained by self-administered questionnaires. The distribution of the individual doses estimated by the Basic Survey was previously presented according to 10-year-step age groups such as 0-9 and 10-19 (age at the time of accident). As far as can be seen from the distribution, dependence of individual dose on the age groups was not so obvious [8], compared with the dose ratios among infants/children/adults presented by the UNSCEAR 2013 report.

In this paper, an average of external doses estimated by the Basic Survey was calculated for each of the three age groups, in accordance with the categories of the

UNSCEAR 2013 report. The dose ratios among the three age groups were compared with those presented in the UNSCEAR 2013 report. Differences in dose by sex were also checked within the same age group.

MATERIALS AND METHODS

Basic survey outline

The study protocol of the Basic Survey was reviewed and approved by the Ethics Review Committee of Fukushima Medical University. Details of the Basic Survey protocol are given elsewhere [7]. Briefly, it is a self-administered questionnaire survey that asked subjects to record and send back information on their behavior (including time spent indoors and outdoors and time of moves) in the 4 months after the accident. Information on types of dwellings and buildings for work places/schools was also collected. Target population of the Basic Survey has been people who were registered residents of Fukushima Prefecture from March 11 to July 1, 2011 (around 2 million people, including children and infants). For children of elementary school age or younger, parents were asked to fill in their children's behavior records. Additionally, for children under the age of 20, parents were asked to sign the questionnaire and verify the information.

The respondents' behavior records were digitalized, and individual estimates of external effective dose were made using a computer program. Details of the computer program including dose rate maps are described elsewhere [9]. Briefly, the program calculates individual effective doses by superimposing the behavior records with daily ambient dose rate maps. The maps were created as a 2km × 2km mesh and the dose rate was assume to be uniform within each mesh area. The dose rate for each mesh area was based on monitoring data released by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan except for the first three days, when the monitoring data were not available. For the first three days, ambient dose rate maps were created based on simulation results of SPEEDI (System for Prediction of Environmental Emergency Dose Information) [(10)]. Hourly effective dose rate maps outputted from the SPEEDI simulations (1km× 1km mesh) were averaged over a day. Furthermore, the effective dose rate maps were reconstructed to have a mesh size of 2km×2km and used for the Basic Survey dose calculation for the first three days. Examples of the dose rate maps can be found on a web page of the Ministry of the Environment, Japan [(11)].

Dose conversion coefficients from ambient dose to effective dose should be different among infants/children/adults due to their body sizes. In the Basic Survey, the external dose for adults is first calculated using individual behavior records, regardless of age of respondents. Then, if the respondent's age is between 1 and 15 years old, the external dose is corrected using C (y):

$$C(y) = -0.0144y+1.27 \qquad (1)$$

For example, the correction factor was calculated to be 1.256 for 1-year-old children and 1.126 for 10-year-old children. In the case of 0 aged infants, however, a correction factor of 1.36 was used [(9)].

Replies to the Basic Survey are still being collected and the dose distributions by area and by age group (10-year intervals) are reported to prefectural meetings periodically. Also, the dose estimates are reported to the respondents, because the Basic Survey was designed to have an important aspect of being a health service to the public [(12)]. In this study, dose estimates completed until March 31, 2018 were used [(13)]. Until then, 465,284 dose estimates (excluding radiation workers) had been completed. Around one third of them were for children (<20y). Usually, Fukushima Prefecture can be divided into seven areas. The distributions of dose estimates for all age groups by area is presented in Fig. 1.

Originally, effective dose was not individual-specific but related to reference persons [14)]. Also, in the present study, the dose calculation is based on the self-administered questionnaires and gamma ray dose rate maps created from available measurement data. Thus, the calculation of individual effective doses in the Basic Survey is considered to have some amount of uncertainty. The dose values by the calculation program have many figures after the decimal point and some rounding was necessary considering the uncertainty. As described before, the Basic Survey has the important aspect of being a health service to residents by providing dose estimates with individuals who provided their behaviors in the questionnaires and submitted them. The rounding was done so that the residents could understand that the provided dose estimates are not very precise. Considering this situation, it was decided that the dose estimate should be rounded to the first decimal place for doses of less than 10 mSv and to the ones place for doses of more than 10 mSv. It was also decided that these rounded dose estimates for the residents should also be used for data for research purposes considering fairness. The rounded values of dose estimates are stored in a database which is open to researchers. In the case of dose values of less than 0.1 mSv, they are stored as “less than 0.1 mSv” without any numerical data. Data used in this study were extracted from the database.

UNSCEAR dose estimation

Details of the dose estimation method adopted by the UNSCEAR 2013 report [1] are described in its Attachment C-12. Briefly, it can be summarized in the following way. A computational model for UNSCEAR dose calculation consists of four sub-models: (a) the estimation of the kerma rate in free air at a reference site in a settlement; (b) the estimation of the location factors defined by the ratio of kerma rates in air at a location of interest to that at the reference site; (c) the estimation of occupancy factors for different population groups at various types of locations; and (d) the estimation of coefficients to convert kerma rate in air to effective dose rate, depending on body size (age group).

The kerma rate in free air at the reference site in the settlement was calculated based on measured deposition density released by MEXT. Systematic monitoring of the deposition density of radionuclides in the vicinity of FDNPP was conducted during June and July 2011; soil was sampled on the basis of a grid of 2-km squares up to distance of 80 km and on the basis of a grid of 10-km squares up to distance of 100 km, and over the remaining area of Fukushima Prefecture. In total, the data from about 2,200 measurements were available. The results of these measurements were included in the dose calculation model. Distribution of deposition density of radionuclides can be found in the UNSCEAR 2013 report [1] Attachment C-6.

Comparison of dose among different age groups

In this study, the respondents to the Basic Survey were divided into three age groups: 0-5 y (representative of 1-year-old infants), 6-15 y (representative of 10-year-old children) and over 15 y (representative of adults) in accordance with the category of UNSCEAR report. The age at the time of accident was used for this categorization. For each of the seven areas, the respondents were categorized into the three age groups and their average doses were calculated. In the calculation, dose estimates of "less than 0.1 mSv" were excluded, because it was not possible to treat them as numerical data. After the exclusion, the dose ratios of 10-year-old children to adults and 1-year-old infants to adults for non-evacuated areas were compared with values presented in the UNSCEAR 2013 report (i.e., 1.4 for 10-year-olds and 1.7 for 1-year-olds). Also, differences in dose between males and females in the same age groups were checked.

RESULTS AND DISCUSSION

The dose ratios of infants/adults and children/adults for the seven areas are shown in Table 1, together with average doses for each age group. The excluded numbers of dose estimates (i.e. number of dose estimates of "less than 0.1 mSv") are also listed. The doses for the Minami-Aizu area, which is far from the FDNPP, were very low, as indicated in Figure 1. For this area, the excluded number of dose estimates was larger than the number of dose estimates that were larger than 0.1 mSv. Thus, Minami-Aizu area was excluded from the comparison. It should be emphasized that doses for infants and children were smaller than those for adults in the Soso area (0.82 and 0.87 times, respectively), while those were larger for the other five areas. Most of the Soso area was designated for evacuation and that seemed to affect the dose ratios (discussed later). The averages of the dose ratio to adults, excluding Minami-Aizu and Soso areas, were 1.08±0.03 for infants and 1.06±0.02 for children (the uncertainties indicate standard deviations for the five areas). They were smaller than the UNSCEAR estimates, i.e. 1.7 for infants and 1.4 for children.

Differences in the dose by sex were investigated among the same age groups and these results are shown in Table 2. The number ratios of male/female were not so different in the same age group among different areas. The dose for males was generally larger by around 10% for adults for each area, while the difference between males and females was within 3% for each group of infants and children.

Differences in dose by age group

Reasons for differences in the dose ratio were considered. As mentioned before, the difference in external dose by age could result from three factors: location factor, occupancy factor and body size factor. First, the body size factors used in the UNSCEAR 2013 report and the Basic Survey were compared, and then the other two factors were discussed.

Body size factor

In the UNSCEAR 2013 report, the body size factor was estimated in two ways. One was to use the effective dose per unit kerma in air 1 m above ground (adults, 0.72; 10-year-olds, 0.80; 1-year-olds, 0.93 in Sv/Gy as recommended values regardless of photon energy) in the case of exposure from an infinite plane source at a depth of 0.5 g/cm^2 in the ground. In this case, the effective dose for 1-year-olds was around 1.3 times larger than that for adults, even if they stayed at a place with the same air kerma rate. For 10-year-old children, it was 1.1 times larger.

The other method was to use values for effective dose rate per unit deposition density of radionuclides which were obtained or derived from Petoussi-Henss et al [15)]. These values differed slightly between radionuclides. In the case of ^{137}Cs, it was 1.69 for 1-year-olds, 1.34 for 10-year-olds and 1.25 for adults in nSv/h per kBq/m^2. Hence, the effective dose for 1-year-old infants was indicated to be around 1.4 times larger than that for adults, if they stayed at a place with the same deposition density area. For 10-year-old children, it was 1.1 times larger.

As mentioned before, calculations in the Basic Survey used Eq (1) for the correction of body size factor: 1.26 for 1-year-olds and 1.13 for 10-year-olds. These were not so different from the UNSCEAR values (up to 10%). Thus, it was considered that the body size factor used could not be the main reason for the difference in the dose ratio.

Location factor

The UNSCEAR 2013 report assumed that people in non-evacuated areas spent their daily life within a settlement which had a single reference value of outdoor ambient dose rate. That is, people's behaviors across multiple settlements with different dose levels were not considered. On the other hand, the Basic Survey used 2km × 2km mesh dose rate maps created from measured outdoor ambient dose rates. If personal behaviors based on the self-administered questionnaires indicated that a person spent his/her daily life in multiple mesh-areas with different ambient dose rates, it was reflected for his/her individual dose. For example, children went to schools during the daytime, while their parents went to workplaces. If outdoor ambient dose rates were different between the school and work sites, this could be a reason for the difference in external dose between children and adults, excluding the body size and occupancy factors. Consideration of people's behaviors in the Basic Survey could be a reason for the differences in the dose ratio between it and the UNSCEAR report.

For the Soso area, the doses for infants and children were smaller than those for adults, although the former should be larger considering the body size factor only. An analysis of behavior records for residents in Iitate Village (one of the deliberate evacuation areas) showed that the accumulated times of stay in Iitate Village were shorter for younger age groups (0-9 years and 10-19 years) than adults (over 19 years) [16]. That is, these younger age groups generally evacuated earlier than other age groups. In non-evacuated areas, infants and children might also be cared for from the viewpoint of radiation protection so that they spent their time in lower ambient dose rate areas, compared with adults. It might be one of the reasons why the dose ratios were smaller than the UNSCEAR estimations.

The location factors used in the Basic Survey and UNSCEAR 2013 report are shown in Table 3. UNSCEAR used time-dependent location factor, but its changes with time were not so large within the first year after the accident. The Basic Survey used location factor values shown in Table 3, except for the first three days when radionuclides were present in the air before depositing onto the ground. In the estimation of the four-month dose, however, effects of using different location factor values for the three days could be small.

Although location factors for different building types seemed to be the same (0.4, 0.2 and 0.1), the ratio of factors indoors to those outdoors were different. As for the UNSCEAR estimations, the factor for the wooden one-to-three story houses to that for outdoors (paved or unpaved surfaces) was from 0.53 (=0.4/0.6) to 0.67 (=0.4/0.75), while it was 0.4 for the Basic Survey. That is, "dose reduction effects" by being indoors were estimated to be higher in the Basic Survey. As the time spent indoors became longer, the estimation of dose reduction effectiveness could be of significance in the total external dose.

Occupancy factor

The last factor considered for possible causes of the dose difference was the occupancy factor. The UNSCEAR 2013 report used the occupancy factor values for indoors as 0.8 for 1-year-olds and 0.85 for 10-year-olds, 0.7 (adults, outdoor workers) and 0.9 (adults, indoor workers or pensioners). Regarding occupancy factors for the adult population, the UNSCEAR 2013 report assumed that about 10% were outdoor workers and about 90% were indoor workers.

The Basic Survey has collected information on types of dwellings, together with that on buildings for workplaces and schools. The information was used for the dose estimations. The Basic Survey obtained behavior records for more than 465,000 residents in Fukushima Prefecture at the time of the nuclear accident. Although no comprehensive analysis on the occupancy factor for these persons has been done yet, average time spent outdoors per day for residents in Iitate Village (included in the Soso area) was previously analyzed [16]. According to the analysis, almost half of the responses from age groups of 0–9 years and 10–19 years indicated that their activities during the stay in Iitate Village were limited to being indoors and moves. However, the average time spent outdoors was longer for middle aged groups. Less time spent outdoors among younger age groups and more time spent outdoors among middle aged groups could result in compensation for the differences in their doses due to the body size factor.

Iitate Village was designated as a deliberate evacuation area and the situation may be different in non-evacuation areas. Reports on occupancy factors for residents after the accident are limited. Some data have been published by Yoshida et al [17]. According to a survey of this report, average time spent outdoors was 1.3 to 2 hours for infants less than 6 years old and 2.7-2.9 h for children between 6 and 15 years old. These corresponded to indoor occupancy factor values of 0.92 to 0.95 for infants and 0.89 for children, which were larger than the values used in the UNSCEAR 2013 report. Also, children aged 6 to 15 years spent 6.3 to 7 h in school buildings on average. Most of them were considered to be made of concrete, which assumed a location factor of 0.1 or 0.2 (Table 3).

Even if the same indoor occupancy time and the same location factor were applied, external doses could be different, depending on average time spent per day for each building type (Table 3). For example, the dose would be different between the following two cases: (1) all of their time indoors (e.g., 20 hours) was spent in wooden one-to-two-story houses and (2) half of their time indoors (10 hours) was spent in wooden one-to-two-story houses and the other half was spent in concrete buildings.

The UNSCEAR 2013 report says "typical adults were estimated to spend 0.6 of their time in wooden one-to-two-story houses and 0.3 of their time at work in concrete multi-story buildings. Typical preschool children were estimated to spend all of their time indoors in wooden houses". How to assign time spent indoors (for wooden and/or concrete buildings) for children aged 6 to 15 does not seem to be mentioned in the UNSCEAR 2013 report. If it is assumed that they spend all of their time indoors in wooden houses, this will overestimate the external dose relative to the actual dose, considering actual time spent in their school buildings.

The survey data by Yoshida et al. were obtained from June 2012 to November 2013 in Miyagi Prefecture, neighboring prefecture of Fukushima. For the first year after the accident (in March 2011) in Fukushima Prefecture, staying outside seemed to be refrained from more, even in non-evacuated areas due to concerns about external exposure [18, 19], especially for children. Thus, times spent outdoors in the first year in Fukushima Prefecture might be shorter than times reported by Yoshida et al.

In summary, the following points were considered as reasons for the differences in the dose ratio among the three age groups between the UNSCEAR 2013 report and the Basic Survey: (1) estimation of average time spent indoors per day (especially, time spent in concrete buildings), (2) estimation of dose reduction effects by being indoors compared with being outdoors, and (3) consideration of people's behaviors across multiple settlements with different ambient dose rate levels. That is to say, the body size factor made doses larger for children/infants than adults, but its influence was similar between the UNSCEAR and the Basic Survey estimations. However, the doses for children/infants which were estimated larger than adults due to the body size factor were partially compensated by the above three factors in the Basic Survey, which led to the smaller dose ratios of infants/adults and children/adults than the UNSCEAR estimation gave.

Differences in dose by sex

As shown in Table 2, differences in dose by sex among the same age group were small (less than 3%) for infants and children, while that for adults was from 1.08 to 1.17 (average: 1.11±0.04) for the six areas (Minami-Aizu was excluded). Statistical data for the 2010 Population Census in Japan reported the working population for separate categories of industries (total of 13 categories) [20]. It was difficult to distinguish outdoor workers and indoor workers from the categories, but people engaged in agriculture, construction and fishery industries can be considered to work outdoors for most of the time. The ratio of population engaged in these three industries to the total working population aged 15 or more was around 22% for males and around 10% for females. That is, the percentage of outdoor workers seemed to be higher for males. This could be the main reason why the dose for males was higher for adults.

Limitations

There are some limitations in this study. First, the Basic Survey estimates external doses for the first four month, while the UNSCEAR estimates the first-year external doses. Personal behaviors after the first four months are not known from the Basic Survey. It is possible that time spent outdoors may increase, along with time passing after the accident, compared with the first four months. Secondly, the response rates for the Basic Survey are not so high, 27.6% for all age groups for the entire prefecture. As suggested from a previous survey [21], however, respondents of each age group were assumed to be representative of all residents including non-respondents of each area. Differences in response rate between the three age groups were not considered in the present study.

CONCLUSIONS

According to the Basic Survey, the first four-month doses for infants and children in non-evacuated areas were 1.08 and 1.06 times larger than those for adults on average. The former two doses were smaller than values estimated by the UNSCEAR report (1.7 for infants and 1.4 for children). In evacuated areas, the ratios were much smaller, 0.82 for infants to adults and 0.87 for children to adults. Because infants and children were considered to be evacuated earlier than adults in these areas, the ratios were much smaller than those in non-evacuated areas.

In non-evacuated areas, the following points were considered for reasons why the dose ratios of the Basic Survey were smaller than those of the UNSCEAR 2013 report: (1) larger average time spent indoors per day (especially, time spent in concrete buildings) for children/infants than the UNSCEAR estimation; (2) higher dose reduction effects by being indoors compared with being outdoors in the Basic Survey; and (3) consideration of people's behaviors across multiple settlements with different ambient dose rate levels in the Basic Survey.

As for difference in dose by sex, it was small for infants and children (less than 3%), while that for adults were around 10%, which could be because the ratio of outdoor worker was higher for males.

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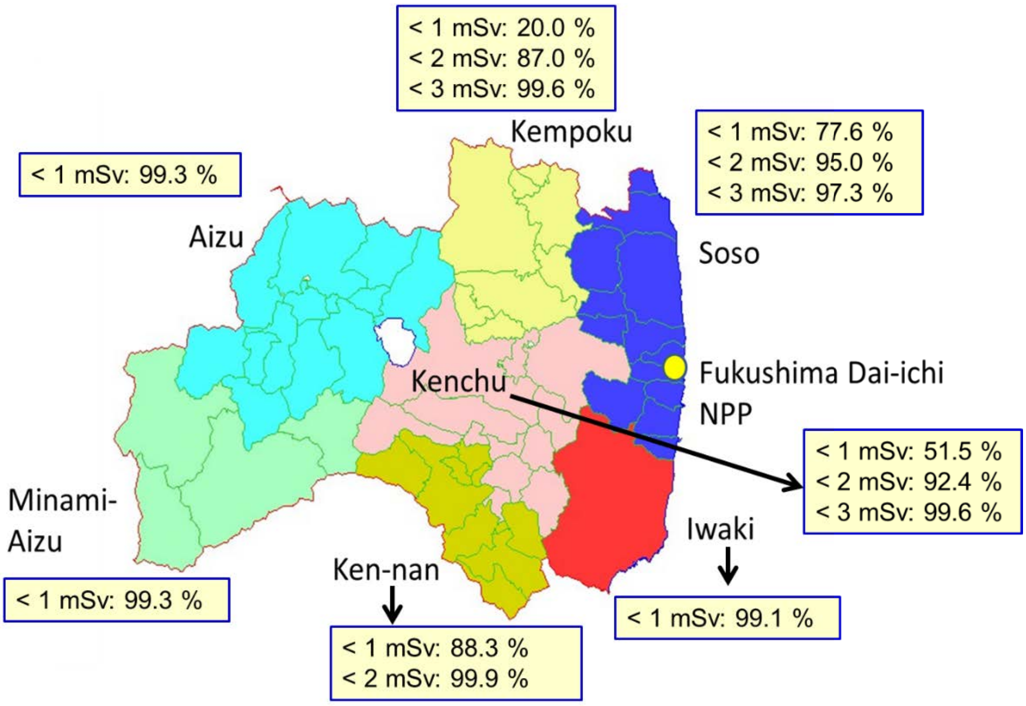

Figure 1. Dose distributions for all age groups by area

Table 1. Average doses for the three age groups and the dose ratios to the adult group

Area	Kempoku			Kenchu			Kennan			Aizu		
Age group	>15y	6-15y	0-5y	>15y	6-15y	0-5y	>15y	6-15y	0-5y	>15y	6-15y	0-5y
Valid number of dose estimates	91,739	20,275	11,710	78,034	20,359	12,438	19,762	5,713	3,355	28,188	10,046	5,475
Excluded number of dose estimates	844	116	281	1,784	275	558	708	93	103	2,086	220	184
Average dose (mSv)	1.37	1.47	1.47	1.00	1.08	1.08	0.58	0.60	0.62	0.24	0.26	0.27
Ratio to adults	-	1.08	1.08	-	1.08	1.08	-	1.04	1.07	-	1.05	1.13

Area	Minami-Aizu			Soso			Iwaki		
Age group	>15y	6-15y	0-5y	>15y	6-15y	0-5y	>15y	6-15y	0-5y
Valid number of dose estimates	1,293	448	256	52,747	7,590	3,778	51,731	11,446	5,720
Excluded number of dose estimates	2,017	660	337	6,025	1,196	844	3,186	691	974
Average dose (mSv)	0.20	0.19	0.17	0.86	0.75	0.71	0.34	0.35	0.36
Ratio to adults	-	0.94	0.85	-	0.87	0.82	-	1.04	1.06

Table 2. Difference in dose by sex

Area	Kempoku			Kenchu			Kennan			Aizu		
Age group	>15y	6-15y	0-5y	>15y	6-15y	0-5y	>15y	6-15y	0-5y	>15y	6-15y	0-5y
Number ratio (Male/Female)	0.80	1.04	1.06	0.78	1.04	1.04	0.82	1.04	1.02	0.81	1.03	1.10
Dose ratio (Male/Female)	1.08	1.01	1.01	1.10	1.01	1.01	1.08	1.00	1.03	1.14	1.03	1.03

Area	Soso			Iwaki			Whole prefecture		
Age group	>15y	6-15y	0-5y	>15y	6-15y	0-5y	>15y	6-15y	0-5y
Number ratio (Male/Female)	0.75	1.03	1.06	0.81	1.05	1.04	0.80	1.04	1.05
Dose ratio (Male/Female)	1.17	1.01	1.01	1.11	1.01	0.99	1.11	1.01	1.01

Table 3. Location factors used in the UNSCEAR report and Basic Survey

UNSCEAR	*T*=0	*T*=0.33 year (4 months)	*T*=1 year
Reference sites (open plot of undisturbed ground)	1	0.93	0.81
Unpaved surface outdoors (lawn, meadow, etc)	0.75	0.70	0.61
Paved surface outdoors (asphalt, concrete, etc)	0.6	0.49	0.33
Inside of wooden one-to-three-story houses	0.4	0.38	0.34
Inside of wooden fireproof one-to-three-story houses	0.2	0.19	0.17
Inside of concrete multi-storey buildings	0.1	0.09	0.08

Basic Survey	*T*=0	*T*=0.33 year (4 months)
Outdoors in settlements (based on time-course measurement)	1	1
Inside of wooden houses	0.4	0.4
Inside of one or two story concrete houses	0.2	0.2
Inside of three or more story concrete buildings	0.1	0.1

T: time after the deposition of radionuclides