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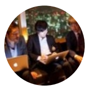

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Comparison between Direct Measurements and Modeled Estimates of External Radiation Exposure among School Children 18 to 30 Months after the Fukushima Nuclear Accident in Japan

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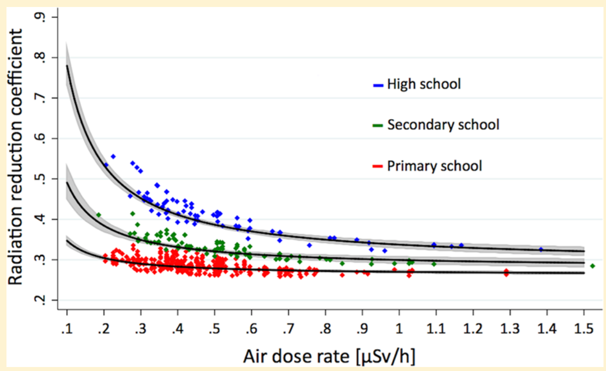
Supporting Information

ABSTRACT: After a major radioactive incident, accurate dose reconstruction is important for evaluating health risks and appropriate radiation protection policies. After the 2011 Japan Fukushima nuclear incident, we assessed the level of agreement between the modeled and directly measured dose and estimated the uncertainties. The study population comprised 520 school children from Minamisoma city, located 20 km north of the nuclear plant. The annual dose 18−30 months after the incident was assessed using two approaches: estimation using the model proposed by the Japanese government and direct measurement by radiation dosemeters. The ratio of the average of modeled and measured doses was 3.0 (standard deviation (SD): 2.0). The reduction coefficient, an index for radiation attenuation properties, was 0.3 (SD: 0.1) on average, whereas the value used in the government model was 0.6. After adjusting for covariates, the coefficient had a significant negative correlation with the air dose rate in the dwelling location ($p < 0.001$), indicating that stronger building shielding effects are valuable in areas with higher air contamination levels. The present study demonstrated that some overestimation may have been related to uncertainties in radiation reduction effects, and that the air contamination level might provide a more important indicator of these effects.



INTRODUCTION

After a major radiation-release incident, radiation exposure is a primary public concern.[1] In these situations, rigorous assessment of the exposure level is fundamental for evaluating the radiation risks to human health and the environment.[2−6] Accurate understanding of the exposure level is also important for properly evaluating the effectiveness of radiation protection policies, such as decontamination activities and evacuation directives, and for assessing the need for establishing further safety precautions.[7]

Radiation exposure can be external (from gamma photons, X-rays, neutrons, or high-energy beta particles emitted from a source outside the body), internal (from sources inside the body), or both external and internal, and the radiation dose can be acquired through various exposure pathways.[8] The effective dose, which is the weighted sum of equivalent doses to various tissues and organs, cannot be measured directly. However, the effective dose can be calculated from alternative operational quantities, such as the personal dose equivalent (Hp(d)) and ambient dose equivalent (H*(d)). The International Commission on Radiological Protection (ICRP) Publication 103 defines

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Hp(d) and H*(d) as "the dose equivalent in soft tissue (commonly interpreted as the "ICRU sphere") at an appropriate depth, *d*, below a specified point on the human body" and "the dose equivalent at a point in a radiation field that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth of *d* on the radius vector opposing the direction of the aligned field", respectively.[9] These dose equivalents are assessed by the following methods: (1) dose reconstruction estimation with reasonable scientific assumptions based on limited available data, or (2) direct individual dose measurements.[10] The dose estimation from external irradiation and inhalation is based on the level of air or soil contamination by considering that exposure attenuation is a function of personal and environmental factors, which are referred to as radiation reduction factors.[10−13] Moreover, the dose from ingestion is estimated based on the amount of contaminated foodstuffs consumed.[10−13] On the other hand, direct dose measurements are performed using an individual radiation dosemeter for determining the external exposure level[14] or using anthropogammametry (i.e., whole body counting (WBC)), which is the best method for determining the amount of radionuclides within the body at the time of measurement.

Although several intergovernmental bodies such as the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the World Health Organization (WHO) have also developed dose estimation models to assess radiation exposure levels and risks to human health,[10,11] there are significant concerns regarding the potential disagreement between direct measurements and modeled estimates of external radiation exposure. This disagreement may exist because of model uncertainties due to limited or incomplete knowledge or information.

For example, for external exposure, the disagreement may come from uncertainty in the radiation reduction functions, which are primarily determined both by the degree of shielding from exposure provided by home, school, or work buildings[15−17] and by human behavior patterns. In addition, the estimation presents individual-, district-, or prefecture-level dose averages for representative members of the public; therefore, there must be uncertainty in how accurately the data used for the estimation represents the spatial distribution of the radionuclides for each measurement level.[14] Other uncertainty sources have been discussed elsewhere.[11,14,18]

However, given that direct measurements can only indicate the individual-level dose at monitored time points, modeled estimates must be used to assess year-long district-level or prefecture-level dose.[18] Therefore, despite possible disagreements between the direct and modeled dose, the modeled estimation is an important exposure evaluation approach for managing the aftermath of a nuclear incident with due consideration of the uncertainties in the estimation.

In response to the Fukushima incident, the city of Minamisoma (located 14−38 km from the nuclear plant), Fukushima Prefecture, launched an external radiation exposure screening program in October 2011 in cooperation with the Minamisoma Municipal General Hospital (MMGH). In this program, the exposure levels of city residents were directly measured by individual dosemeters. Using this data, we (1) assessed the agreement between the modeled and measured levels of the annual external exposure in terms of the effective dose 18−30 months after the Fukushima incident and (2) estimated the uncertainties in the Japanese government's dose estimation model leading to the potential disagreement with the measured dose.[15] Through the present study, we aim to add further evidence for sources of uncertainties in the assumed exposure scenarios used in the dose reconstruction models. These uncertainties should be essential for evaluating radiation exposure after a major radiation-release incident, which will help the government, local authorities, health planners, and disaster coordinators to develop well-optimized radiation protection policies.

■ MATERIALS AND METHODS

Ethics Statement. Ethical approval for this study was granted by the ethics committee of the MMGH, Japan, under authorization number 25-08. The ethics committee agreed that written consent was not required for each participant in the research study. The original participant data contained personally identifiable location information (longitude and latitude), but the data was subsequently anonymized and deidentified prior to the data analyses by replacing the location information with the air contamination level at that location (see "Location-Specific Air Dose Rate").

Data Collection. *Settings and Populations.* In response to the Fukushima nuclear incident, the city of Minamisoma launched a voluntary external radiation exposure screening program in October 2011 in cooperation with Chiyoda Technol Corp., Japan, a manufacturer of radiation protective products. This program is free of charge for infants, school children, and pregnant women who are registered in the Minamisoma family registry. The program notification was sent to each school, and the information is also disseminated using the city's public magazine.

The screening program was conducted once every three months. In the program, the city office sends a radiation dosemeter (Glass Badge: GD-450, Chiyoda Technol Corp.) to the program participants. The initial screening program was conducted between October 1, 2011, and December 19, 2011. During the screening, the participants are instructed to hang the dosemeter from their neck to measure their external dose for three months. At the time of measurement, note that levels of internal radiation exposure appear to be marginal among most Minamisoma residents,[2,3,19−22] therefore, the possibility that the Glass Badge measured radiation from internal radionuclides would be negligible. After the measurement, the dosemeters are returned to the city office, and MMGH records the measured doses.

To assess the adherence to equipment instructions, when the Glass Badge is returned, we survey the participants on the conditions that Glass Badge was worn, including the number of hours that participants wore the badge on school days and weekends and in what situations. At this time, we also assess other participant behavior patterns during the measurements, for example, school commuting time and means, and time spent outdoors after school or on a weekend.

In the present study, we considered the data for all primary, secondary, and high school children (aged 7−12, 13−15, and 16−18, respectively) that participated in the fourth screening program, which took place between September 1, 2012, and November 31, 2012 (n = 1956). The collected Glass Badge data includes the three-month measured dose and the basic demographic characteristics of the participants, such as sex, school-level, and dwelling area (rural area or urban area). The urban area was defined as an area with 4000 people per square kilometer. In addition, we obtained their home location

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information (longitude and latitude). The dose attributed to natural sources, including the universe (cosmic rays) and compounds within the earth, was subtracted from the measured value by default. These subtracted values were set as 0.21 mSv/year (0.024 μSv/h) from the universe and 0.33 mSv/year (0.038 μSv/h) from the earth, which were the average values obtained from 20 Glass Badges with a measurement time of 35 days that were placed at Oarai, Ibaraki Prefecture, Japan, before the incident. The range of the measurement accuracy of the cumulative dose in 35 days was only ±4%. Therefore, the Glass Badge data we collected is referred to as the additional dose after the Fukushima incident.

Measured Annual Additional Effective Dose. To express additional dose in terms of annual levels, we simply multiplied the three-month measured values by four. The outcome of the Glass Badge measurement is a dose equivalent at a tissue depth of 1 cm (Hp(10)). The Hp(10) values obtained in the geometrical conditions of the affected areas in the Fukushima Prefecture are known to be comparable with the effective dose of isotropic (ISO) or rotational (ROT) irradiation geometries,[18,23−25] which enabled us to standardize the outcome measurements between the measured and modeled dose. Note that effective doses are principally not measurable. Therefore, operational quantities for dosemetric measurements are generally used, which enable a sufficiently accurate dose determination with satisfactory information on the radiation fields and with considerations of various radio-sensitivity of different organs/tissues (and body shielding if individual dosemeters are used).[25,26]

Modeled Annual Additional Effective Dose. *Estimation Model.* We used the following model developed by the central government to estimate the annual additional effective dose, E_i [mSv/year], for a person of age k at dwelling location i:

$$E_{i,k} = (D_i - D_{\text{nat}}) \times F_k \times (T_{\text{out}} + T_{\text{in}} \times \beta) \times 24 \times 365$$

where D_i is the air dose rate [μSv/h] at location i at a height 1 m above flat ground; D_{nat} is the air dose rate [μSv/h] from natural sources; F_k is the conversion coefficient from the air dose rate to the effective dose for a person of age k; T_{out}, and T_{in} are fractions of time spent outdoors and indoors in a day, respectively; and β is the shielding coefficient, which is referred to as the ratio of the on-site indoor-external radiation level to the on-site outdoor-external radiation level.

Then, we employed air dose rate data obtained by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) for D_i, which includes the natural dose only from the earth (the details of this value are discussed in the next section). We used the value of 0.04 μSv/h for D_{nat}, which is a preincident national average of exposure from the earth. The fraction of the time spent outdoors, T_{out}, and the time spent indoors, T_{in}, were set at 8/24 and 16/24, respectively, and the shielding coefficient β was set to 0.4. Age was not taken into account, and the conversion coefficient F was set to 1.0. These values, including the values for D_{nat}, are the same values used by the government.[13] In this model, the radiation reduction coefficient refers to $T_{\text{out}} + T_{\text{in}} \times \beta$, that is, 0.6.

Location-Specific Air Dose Rate. To assess the air dose rate at a height of 1 m above ground, MEXT has conducted airborne monitoring in contaminated areas. At the end of 2013, the monitoring was performed six times within an 80 km radius of the nuclear plant. The flight altitudes were approximately 300 m above the ground, and the values expressed by the monitoring are the averages of the measured values in approximately 600 m diamater circles below the aircraft. The width of the track was about 1.85 km. The air dose rates are measured in terms of the ambient dose equivalent (H*10)[27] and include only the natural dose from the earth. Monitoring results are open access, and the data contains the air dose rates [μSv/h] and the associated monitoring points (longitude and latitude).

To calculate the air dose rate at the middle date of the fourth Glass Badge screening program, which occurred between September 1, 2012, and November 31, 2012, we used a time interpolation method on the data from fifth and sixth MEXT monitoring programs, which measured air dose rate on June 28, 2012, and November 16, 2012, respectively.[28,29]

The air dose rate at dwelling location i was assessed using the following methods. The dose rates at each monitoring spot were averaged by a 500 m^2 mesh based on the Japan Profile for Geographical Information Standards (elevation and slope angle fourth mesh data) released by the Ministry of Land, Infrastructure and Transport.[30] Then, the dwelling location i was defined as a mesh area where the participant's home is located. Therefore, each screening participant belongs to one of the mesh areas, which enabled us to estimate participant-specific modeled effective dose using the equation above.

Data Analysis. *Measurement Error Adjustment for Measured Dose.* Given that the presence of measurement errors would cause biased parameter estimates and lead to erroneous analytical outcomes to various degrees,[31] we first adjusted for measurement errors in the measured dose, by introducing error-corrected estimates based on the regression predictions approach. Namely, we replaced the "raw" Glass Badge measurements of the annual dose with the predicted values from the regression. This "adjusted" measured dose was applied in all following data analyses. Due to the imprecision of the Glass Badge measurements, the "raw" measured dose of some participants was below zero after automatically subtracting the background doses; hence, for the adjustment, we employed the Tobit multiple regression models, which estimate the linear relationships between the model parameters by adjusting for the left-censoring effect of the Glass Badge. Then, the "raw" Glass Badge measurements of the annual dose were regressed against the demographic characteristics of the participants, such as sex, school-level, and dwelling area, as well as the air dose rate at dwelling location, which were assumed to be associated with measurement errors.

Ratios of Modeled versus Measured Dose. To assess the level of agreement between the modeled and measured values of the annual effective dose, the ratio of the modeled to measured doses was calculated for each participant. Given the quantization error of the Glass Badge measurements and the MEXT monitoring, an accuracy of two significant digits was accepted to present the results. Mean ratios in different groups, such as sex, school-level, and dwelling location, were compared using a t test and ANOVA, where p-values less than 0.05 were regarded as significant.

Radiation Reduction Coefficient. The government's dose estimation model employs a radiation reduction coefficient of 0.6 uniformly across all populations under the assumption that people spend 8 h outside and 16 h inside in a building with a shielding effect of 0.4 in a day. However, different radiation attenuation functions were expected for the characteristics of different residents, which may lead to different ratios of the modeled to the measured doses among the study participants.

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Then, to examine the potential variability in the reduction coefficient for the participants, we calculated each participant's reduction coefficient using the following equation:

$$R = G \div ((D - D_{\text{nat}}') \times F_k \times 24 \times 365)$$

where R is the radiation reduction coefficient; G is the regression-adjusted Glass Badge measurements of the annual dose [mSv]; and D is the air dose rate [μSv/h] measured by the MEXT monitoring at each participant's dwelling. We employed 0.05 μSv/h for D_{nat}, which is a preincident Minamisoma city-specific average of the background dose from the earth [μSv/h].[27] Given that the radiation shielding effects of body tissues depend on body size, the conversion coefficient from the ambient dose equivalent to the effective dose increases as age decreases, according to Yamaguchi et al.[32] Therefore, the conversion coefficient for the age group of this study (7−18) was obtained from the following linear function of age k, which was expressed and validated by the National Institute of Radiological Sciences (NIRS), Japan:[33]

$$F_{k<16} = F_{k\geq 16} \times (-0.0144 \times k + 1.27)$$

The conversion coefficient for those participants over age 16, $F_{k\geq 16}$, was set to 0.6.[33] Next, the reduction coefficient distribution among the participants was visualized using histogram charts and univariate kernel density estimation, which was based on a Gaussian kernel with an optimal bandwidth.

Finally, a multiple linear regression model was developed to estimate the associations of the radiation reduction coefficient with the characteristics and behavior patterns of the participants during the measurements, adjusting for different equipment adherence. School-specific contamination levels (i.e., air dose rate at a height 1 m above the ground within the school grounds, at main gate, and at the entrance/exit) measured in terms of ambient dose equivalent (H*10) were also incorporated into the model. These school-specific contamination levels, which included only the natural dose from the earth, were monitored by the Fukushima Prefecture.[34] The final model was used to predict the adjusted reduction coefficient, which was plotted against significant variables to allow for visual inspection of their associations. The regression model construction in these analyses was based on a backward-stepwise procedure with p-values greater than 0.05 removed. The heteroskedasticity of the residuals in the model was examined using the White and Breusch-Pagan tests.

The spatial data formatting and analyses were conducted using R 3.0.2, STATA/MP 13, and ArcGIS 10.2.

RESULTS

Subject Characteristics. We excluded participants who had omitted basic characteristic data or who lived outside Minamisoma city or adjacent areas to avoid misbalancing the unobserved participant characteristics and behavior patterns among different dwelling regions (n = 298). After excluding these participants, a total of 1658 children remained. We then excluded children with low adherence to the equipment instructions, such as those who did not wear the Glass Badge during school commuting hours or while outdoors (n = 1138). Therefore, 520 children were analyzed, representing approximately 13% of all school children in the city at the time of the measurement.

Table 1 describes the subject characteristics and mean values of air dose rate in dwelling location including natural radiation background, measured and modeled annual effective dose, and ratios of the modeled to measured doses. The air dose rate [μSv/h] ranged from 0.2 to 1.5 (mean 0.5, standard deviation (SD) 0.2). The inner-quartile range of the measured and modeled dose is demonstrated using box plots (Supporting Information (SI) Figure S1). The annual radiation effective dose 18−30 months following the incident was 0.8 mSv (SD 0.3) for direct measurement and 2.4 mSv (SD 1.0) for the modeled estimation on average.

Table 1. Air Dose Rate at Dwelling Location (μSv/h), Annual Modeled/Measured Dose (mSv), and the Ratios of the Average Dose

characteristics	number	air dose rate (SD)	modeled (SD)	measured (SD)	ratios (SD)
sex					
male	235	0.5 (0.2)	2.4 (1.1)	0.8 (0.3)	3.1 (1.7)
female	285	0.5 (0.2)	2.3 (1.0)	0.8 (0.3)	3.0 (1.5)
school-level					
primary	344	0.5 (0.2)	2.3 (0.9)	0.7 (0.3)	3.2 (1.5)
secondary	95	0.5 (0.2)	2.6 (1.1)	0.9 (0.3)	2.9 (1.6)
high	81	0.5 (0.2)	2.5 (1.3)	1.0 (0.4)	2.6 (1.6)
dwelling area					
rural	369	0.5 (0.2)	2.5 (1.2)	0.8 (0.4)	3.1 (1.8)
urban	151	0.4 (0.1)	2.1 (0.4)	0.8 (0.1)	2.8 (0.7)
total	520	0.5 (0.2)	2.4 (1.0)	0.8 (0.3)	3.0 (1.6)

Ratios of Modeled versus Measured Annual Effective Dose. The modeled annual effective dose was higher than the measured dose in 95.00% of the participants. The ratio of the average of modeled dose to the average of measured dose among the participants was 3.0 (SD 1.2) (Table 1).

Radiation Reduction Coefficient. The mean reduction coefficient was 0.3 (SD 0.1). Figure 1 shows the histogram of the reduction coefficient with school-level specific kernel density functions. Overall, no participants had a reduction coefficient more than 0.6, which is the value used in the government dose estimation model under the assumption that people spend 8 h outside and 16 h inside in a building with a shielding effect of 0.4 in a given day.

The survey results of participant behavior patterns during the Glass Badge measurements including equipment adherence are explained in SI Table S1. Regarding the time spent outdoors, most of the participants answered less than 2 and 4 h for time spent outdoors after school (97%) and on a weekend (85%), respectively, which is significantly different from the government assumption that people spend 8 h outdoors.

As for school-specific radioactive contamination levels, the air dose levels at school were substantially lower than those at participants' dwellings (SI Table S2). These parameters were considered in the regression model.

The results of the multiple linear regression analysis are shown in Table 2. Because the White and Breusch-Pagan tests showed significant results (p < 0.001 for both), indicating that heteroskedastic residuals were present in the model, robust Huber-White standard errors were employed to establish sufficient statistical significance to allow for heteroskedastic residuals. The following variables were incorporated into the final analysis model: reciprocal-transformed air dose rate, school-level, sex, behavior patterns (i.e., the floor in the home

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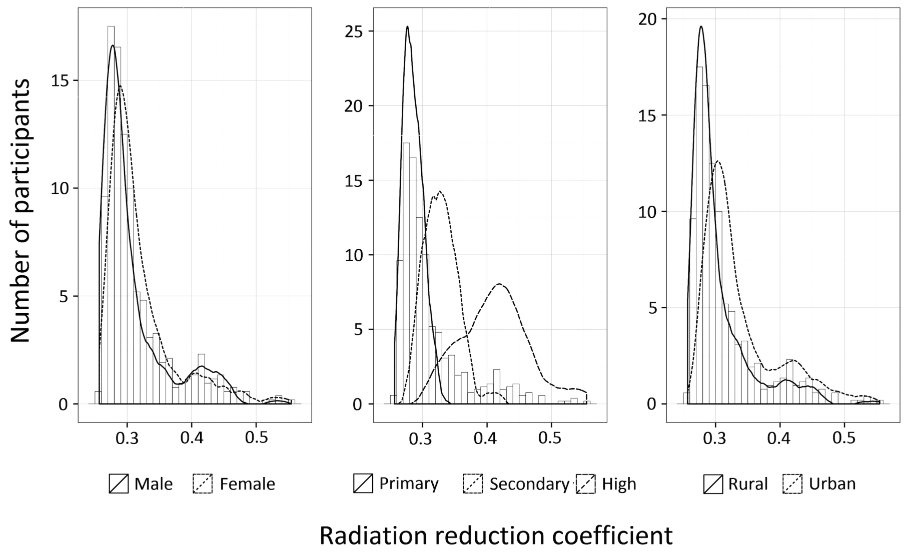

Figure 1. Histogram of the radiation reduction coefficient with school-level specific kernel density functions.

where participants spend the majority of the daytime hours and where they sleep at night, commuting time, and time spent outdoors after school or on weekends), adherence indicators (i.e., hours the Glass Badge was worn on a school day and during the weekend), air dose rate in school grounds, and whether soil surface decontamination had been completed in the school. We observed a substantial negative correlation of the reduction coefficient with the air dose rate ($p < 0.001$), which may indicate that stronger building shielding effects work in areas with higher air contamination levels. There were also slight differences in school-level (coefficient: 0.05 for secondary school children ($p < 0.001$) and 0.13 for high school children ($p < 0.001$) in reference to primary school children) after adjusting for behavior patterns, including time spent outdoors after school or on weekends. This implies that secondary and high school children might be exposed to more radiation than primary school children due to unobserved/unadjusted school-level-specific factors, such as extracurricular activities, including clubs and sports. Sex and air dose rate in the school ground had also significant relationships with the reduction coefficient, but their degrees were nearly zero.

Figure 2 shows the regression prediction of the adjusted radiation reduction coefficient against air dose rate. Because we observed substantial associations of the reduction coefficient with school level, the prediction estimates were established based on the subgroup approach by school-level. The radiation reduction coefficient tended to converge at some levels as the air dose rate increased. Regarding lower air dose rates (less than around 0.2−0.3 μSv/h), there was a considerable shift of the reduction coefficient.

DISCUSSION

This is the first study after the 2011 Fukushima Daiichi nuclear incident in Japan that individually compared radiation exposure levels directly measured by radiation dosemeters and those reconstructed by the Japanese government-proposed equation model. Furthermore, this study estimated potential causes of the disagreement as well as uncertainties in the estimation. We observed that there was a 3-fold disagreement on average between the modeled and measured additional exposure 18−30 months after the incident among the study participants in the city of Minamisoma. Our work, therefore, addressed the critical issue of the government's overvaluation of the dose assessment and the uncertainties associated with the dose estimation.

In this study, we provide information about the causes of the disagreement between the modeled and measured values of the annual effective doses as well as uncertainties in the estimation. First, the government model employs 1.0 as the conversion coefficient from the air dose to the effective dose without considering the varying sensitivity of different organs and tissues to radiation. However, several studies confirmed that the conversion coefficient should be less than 1.0. For example, the conversion should be 0.6 for air dose rates measured in terms of ambient dose equivalent (H*10) for adults according to Saito et al.[33] and NIRS,[35] and 0.7−1.0 depending on age for air dose rates measured in terms of air absorbed dose according to UNSCEAR.[10]

The second potential cause in the difference comes from uncertainties about the radiation reduction coefficient. Japan's government model used 0.6 for the reduction coefficient under the assumption that people spent 8 h outside and 16 h inside in a building with a shielding effect of 0.4 in a day. However, this survey showed that most of the participants answered less than 2 and 4 h for time spent outdoors after school (97%) and on a weekend (85%), respectively, and 100% of the participants had a coefficient of less than 0.6 (Figure 1), implying that the "true" reduction coefficient should be much lower. The regression analysis demonstrated a substantial negative correlation of the reduction coefficient with the air dose rate in participants' dwellings, indicating that stronger building shielding effects work in areas with higher air contamination levels. Supportive evidence on this finding comes from the 2014 joint study between NIRS and the Japan Atomic Energy Agency (JAEA) in which they also reported the potential negative correlation of the building shielding effects with the air dose rate regardless of the building type.[18]

In addition, there were significant associations between school-level with the coefficient after adjusting for covariates, suggesting that behavior patterns in school are also important indicators for the estimation of radiation exposure.[36]

Limitations. The present study has a several limitations. First, we measured the three-month effective dose using a Glass Badge and multiplied the resulting dose by four to obtain an

Table 2. Multiple Linear Regression Model of the Relationship between the Radiation Reduction Coefficient and the Demographic Characteristics and Behavior Patterns of the Participants

variable	coefficient	*p*-value	95% confidence interval
air dose rate [μSv/h] (reciprocal form)	0.02	<0.001	0.01−0.02
school-level			
primary	ref.		
secondary	0.05	<0.001	0.04−0.05
high	0.13	<0.001	0.12−0.14
sex			
male	ref.		
female	0.01	<0.001	0.01−0.01
floor of room where most daytime hours were spent			
first floor	ref.		
over second floor	0.00	0.3	0.00−0.01
floor of sleeping location			
first floor	ref.		
over second floor	0.00	0.6	0.00−0.01
commuting time [h]			
less than 0.5	ref.		
more than 0.5	0.00	0.3	-0.01−0.00
time spent outdoors after school [h]			
less than 0.5	ref.		
0.5−1	0.00	0.4	-0.01−0.00
1−2	-0.01	0.2	-0.02−0.00
more than 2	0.00	0.4	-0.02−0.01
time spent outdoors on a weekend [h]			
less than 0.5	ref.		
0.5−1	0.00	0.6	-0.01−0.00
1−2	0.00	0.9	-0.01−0.01
2−4	0.00	0.3	-0.01−0.00
more than 4	0.00	0.7	-0.02−0.01
hours worn on a school day	0.00	1.0	0.00−0.00
hours worn on a weekend	0.00	1.0	0.00−0.00
air dose rate in school ground [μSv/h]	0.00	<0.001	0.00−0.00
soil surface decontamination			
not completed	ref.		
completed	0.01	0.2	0.00−0.02

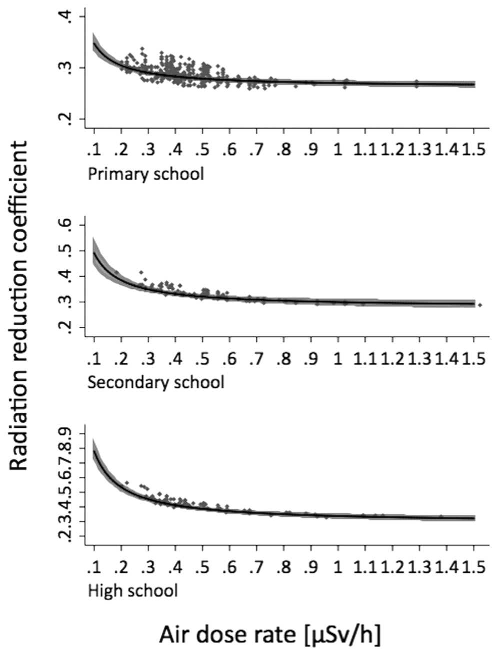

Figure 2. Regression prediction of the adjusted radiation reduction coefficient with 95% confidence bounds separated by school-level.

annual dose; therefore, this method ignored the nature of radioactive decay or disintegration (i.e., half-life) of radionuclides during the subsequent nine months, which might lead to a potential overvaluation of the annual dose. Similarly, the government equation model also does not consider the half-life of radioactive elements. However, the majority of radionuclides released from the Fukushima nuclear power plant are Iodine-131 (500 PBq), Cesium-134 (10 PBq), and Cesium-137 (10 PBq),[37] and their radioactive half-lives are 1 week, 2 years, and 30 years, respectively. Then, given that dose attributed to Iodine-131 and Cesium-134 is negligible or modest, respectively, at the time of the study (18−30 months after the incident) due to their short half-life,[11,14] this constraint might not be very serious. In addition, because Cesium-137 has such a long half-life, the radioactive decay during nine months was marginal.

The second limitation comes from the accuracy of air dose rates measured by MEXT airborne monitoring. The MEXT air dose rates at a height 1 m above ground were measured from a height of 300 m. However, a clear positive correlation with an absolute error of approximately 10−30% in the dose rates between the aircraft measurements and direct ground surveys was demonstrated by JAEA.[38] In addition, the MEXT air dose rates were averaged in 600 m diameter circles below the aircraft. Therefore, given that the spatial distribution of the radionuclides varies from location to location, the accuracy of the measurements might be influenced by environmental characteristics within each measurement area, such as the presence of geographical gradients and forests. However, because the city of Minamisoma is located on the coast with small geographical gradients and because the study participants were living in residential areas (data not shown), this limitation could be ignored.

Third, because the study participants were school children whose daily lifestyle and living environment might be different from other population groups, we cannot generalize the results of this study to the whole population.

Finally, it must be noted that this study is voluntary, and only those who properly measured their dose with good adherence to the dosemeter equipment rules were included in the analyses, which represented 13% of total children in Minamisoma. Therefore, people who have been concerned with radiation exposure might be more likely to be included in the study. Given that people who care about their exposure level might be more likely to undertake additional countermeasures to reduce their risk of exposure in their daily life, which could not be monitored by our behavior surveys nor adjusted for in the analyses, our study may concern selection bias that cannot be ignored. As a result, the ratio of the average of the modeled and measured dose and the radiation reduction coefficient might slightly be overestimated (i.e., higher and lower than the "true" values, respectively).

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Major Implications. Currently, several local authorities, including the Fukushima prefecture, have established direct measurement services for external and internal radiation exposure. Although the use of such direct measurements is beneficial and desirable for reflecting person-specific characteristics, they can only indicate the individual-level doses at the time that people were monitored. Therefore, with due consideration of the uncertainties in estimation, the modeled dose assessment must be an important evaluation approach for assessing the year-long district-level or prefecture-average exposure.[18]

The government aims to provide realistic estimates of dose to the Japanese population depending on the available information, but the present study indicated that some overestimations likely occurred as a result of the undervalued conversion coefficient and uncertainties in the radiation reduction coefficient due to lacking knowledge and information. We suggest that the air contamination level in dwellings and the behavior patterns of people in school where they spend the majority of their daytime hours should be the primary considerations for dose estimation. Because reliable dose estimation is important for improving the response to any major radiation-release incident, further efforts for determining the best available model and investigating additional sources of uncertainties should be performed.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The details of the survey results on participant behavior patterns during the Glass Badge measurements are provided in SI Table S1, while SI Table S2 describes the school-specific radioactive contamination levels. A box plot of the measured/estimated dose distribution is presented in SI Figure S1. This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

All authors were responsible for the study concept and design. M.T., R.H., Y.K., and T.O. acquired the data, which was analyzed and interpreted by all authors. S.N. and M.T. drafted the manuscript, which was critically revised by all authors. S.N. and D.Y. performed the statistical analysis. Y.K. and T.O. provided administrative, technical, or material support. R.H., T.F., M.K., and T.O. were the study supervisors. All authors approved the final draft of the manuscript.

Notes

The authors declare no competing financial interest.

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