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Distribution of radon concentrations in child-care facilities in South Korea

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ABSTRACT

This study was conducted to provide fundamental data on the distribution of radon concentrations in child day-care facilities in South Korea and to help establish radon mitigation strategies. For this study, 230 child-care centers were randomly chosen from all child-care centers nationwide, and alpha track detectors were used to examine cumulative radon exposure concentrations from January to May 2015. The mean radon concentration measured in Korean child-care centers is approximately 52 Bq m^{-3}, about one-third of the upper limit of 148 Bq m^{-3}, which is recommended by South Korea's Indoor Air Quality Control in Public Use Facilities, etc. Act and the U.S. Environmental Protection Agency (EPA). Furthermore, this concentration is about 50% lower than 102 Bq m^{-3}, which is the measured concentration of radon in houses nationwide from December 2013 to February 2014. Our results indicate that the amount of ventilation, as a major determining factor for indoor radon concentrations, is strongly correlated with the fluctuation of indoor radon concentrations in Korean child-care centers.

1. Introduction

Radon is a radioactive gas continuously generated from natural decay of ^{238}U in soils, rocks, and water. Several studies on people exposed toradon (^{222}Rn) confirmed that radon in homes and workplaces poses a serious health risk (WHO, 2005, 2009; ICRP, 2007; AGIR, 2009; UNSCEAR, 2009). Moreover, the risk of developing lung cancer increases for those who have experienced long-term exposure to high concentrations of radon, which causes pathological changes in the function of the respiratory system. This risk was reported to depend on the indoor radon concentration, exposure time, and building ventilation (Neuberger and Gesell, 2002; Lazar et al., 2003). The half-life (3.82days) of radon is sufficiently long for the gas to spread from its source and accumulate in enclosed indoor spaces. Thus, radon is known to potentially be the most dangerous radioisotope. Radon is released from the soil in a gaseous state and can enter buildings through cracks in concrete floor sand walls, holes in floors, drainage pumps, construction joints, and small cracks or holes in hollow block walls. When radon enters a closed space and becomes concentrated, it may reach levels hazardous to public health (Kurnaz et al., 2011). Radon and its decay products concentrate in underground mines, caves, basements, or inadequately designed buildings with poor ventilation, which may cause severe health problems. Thus, information about the radon concentration in residences is important for assessing health risks or when deciding the design of control strategies (Singh et al., 2006).

Children may be more vulnerable to environmental exposure than adults. Since children are in a growing stage, the respiration rate per unit weight in children is higher than that in adults (Patriarca et al., 2000). Accordingly, the U.S. Environmental Protection Agency (EPA) suggested that radon exposure in schools, child-care centers, and nursery facilities could be an issue, and after randomly choosing 927 schools across the United States in 1990, it has been conducting radon mitigation projects in schools and children's activity spaces (US EPA, 1993; 1994). In South Korea, however, no follow-up investigation on the state of radon concentrations in elementary schools has been carried out since the one conducted on a nationwide scale for elementary schools and government offices from 2008 to 2009. Moreover, there has been

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no government-guided survey on radon concentrations in child-care centers.

To provide fundamental data for future radon reduction and management in children's activity spaces in South Korea, this research was conducted to collect data on radon levels in child-care centers inferred from radon concentrations obtained through different methods such as government surveys on the state of radon in dwellings nationwide.

2. Materials and methods

Child-care centers for this study were randomly selected from among child day-care facilities listed in the Private Child Care Association database and the database of day-care facilities in which the 2014 indoor air quality surveys were performed by the Institutes of Health Environment in South Korea. Child-care centers were asked through phone interviews whether they would participate in this research, and those who agreed to participate were selected as target facilities for a first round of sampling.

The measurements in each targeted child-care center were taken in two selected classrooms where children would spend the day. The following principles were applied when selecting the target measurement location. 1) Two classrooms where children spend the day in the target child-care centers shall be selected as measurement locations. 2) All measurement locations shall be on the first floor or lower. However, if there is no activity space on the first floor, the second floor or higher can be examined, and if it is determined that the radon concentration on or above the second floor is high, such classrooms shall be included as measurement locations. 3) If the activity space is located in the basement, the basement activity space shall be routinely selected as a measurement location, and the ground floor (first floor) in the same building shall also be selected as a measurement location. 4) The detector shall be located at the center of the selected activity space, and if this location is in the path of air currents (from a window, ventilator, etc.), a location that is not affected by the air current shall be selected instead. In the case where it was impossible to conduct the investigation according to these principles, field researchers selected a target location that best conformed to the location selection principles.

Radon concentrations were measured using a passive radon detector, Raduet Model RSV-8 alpha track detector (Radosys Inc., Budapest, Hungary) to examine the cumulative exposure concentration for three months. One of the advantages of this detector is that it can measure both radon and thoron (^{232}Th), and thus obtain data on thoron concentrations in addition to radon concentrations. Furthermore, selecting this detector will allow future data sharing as it has been used by the Ministry of Environment of South Korea in the nationwide survey of radon concentrations in houses.

The detectors were installed between January and February 2015 and were exposed for three months before they were collected between April and May 2015. The collected detectors were sealed to prevent airflow into the detector and then transported to the National Institute of Environmental Research for analysis. The sensing elements were dismounted from the collected detectors and submitted to the pre-processing stage. The obtained track was evaluated under a microscope to calculate radon concentrations. Automated equipment (Radosys, Hungary) was used in the pre-processing and track calculation stages. The sensing elements in the detector was chemically etched in 6.25 M NaOH solution at 90 °C for 3 h and 40 min and then neutralized in 1% acetic acid solution for 20 min. After drying at room temperature for one day as a pre-processing step, the track was calculated. The track generated by alpha particles was calculated using an automatic reader and the density of the track was used to calculate radon concentrations using Eqs. (1) and (2).

$$\mathbf{RAC} = \mathbf{EXP}_{Rn} \times \frac{\frac{\mathbf{1000}}{\mathbf{24}}}{T} \quad (1)$$

$$\mathrm{EXP}_{Rn} = \mathrm{CF} \times (\mathbf{1.00} \times RnD - \mathbf{0.02} \times TnD), \quad (2)$$

where RAC is radon activity concentration (Bq m^{-3}),$\mathrm{EXP_{Rn}}$ is the exposure value for the Rn-channel (kBqhm^{-3}),T is the time of exposure in days, CF is the calibration factor provided by the Radosys QC system, *RnD* is the track density counted for the Rn-channel (mm^{-2}), and*TnD* is the track density counted for the Tn-channel (mm^{-2}).

In order to increase the reliability of the obtained results, duplicate detectors and blank detectors were installed in eight measurement locations. The duplicate detector was used to assess the difference in radon concentration levels between two radon detectors installed 30 cm apart in the same place. The blank detector, unpacked, was placed at the same measurement location as the main detector and was collected and analyzed in the same manner as the main detector; obtained values were used to correct for concentration differences. The differences in measured radon concentrations between the main detector and the duplicate detector were verified with the paired *t*-test and relative percent difference (RPD). The RPD represents the ratio of relative differences between a pair of measurement equipment values used in the duplicate measurement. It was calculated using the following equation (US EPA, 1997):

$$\mathbf{RPD}(\%) = [|x_1 - x_2|]/x_{ave} \times \mathbf{100}, \quad (3)$$

where x_1 is radon concentration of the main detector (Bq m^{-3}), x_2 is radon concentration of the duplicate detector (Bq m^{-3}),and x_{ave} is the average radon concentration of the main detector and duplicate detector (Bq m^{-3}).

As discussed above, the study was conducted at 470 sites in 235 child-care centers. However, due to the loss of detectors or errors in the analysis at 30 sites in five child-care centers, radon concentrations were ultimately obtained from 440 sites in 230 child-care centers. In addition, one of the eight duplicate detectors was lost, and thus, the results from seven duplicate detectors were used in the analysis. The buildings were classified as single type and multi-unit type. A single type building refers to a child-care center placed in a detached building or a small child-care center run by a household in an apartment unit, whereas multi-unit type refers to a child-care center located within a building complex. The year of construction was used as an indirect indicator of deterioration, and it was assumed that the older a building was, the more severe the deterioration of the building was. Mean radon concentration levels were compared by classifying the buildings into three groups based on construction year.

To identify factors affecting variations in indoor air radon concentration levels in child-care centers, the questionnaire used by the Ministry of Environment in the nationwide survey of radon concentration in houses was adapted for the child-care centers selected in the present study. The self-administered surveys were conducted by field researchers and were answered by child-care instructors or facility managers. Among the survey questions, those that were considered determining factors of indoor radon concentrations in child-care centers were selected, and the average radon concentrations was compared through Student *t*-test and analysis of variance (post hoc-Duncan analysis). In order to provide fundamental data on the reduction of radon concentrations in child-care centers, an analysis of covariance was conducted to derive the environmental factor that contributes the most to the variation in radon concentrations while controlling other environmental impact factors.

3. Results

Tables 1 and 2 show the paired *t*-test and RPD (%) between radon concentrations obtained from the main and duplicate detectors. The average radon concentrations obtained from the main and duplicate detectors are 105 ± 54 Bq m^{-3} and 107 ± 57 Bqm^{-3}, respectively, showing no statistically significant difference; the average RPD value was also low at 7.6 ± 5.5%. Therefore, the concentrations measured by the detectors used in this study represent the radon concentrations at the measurement locations.

Fig. 1 is the histogram of the radon concentrations measured in the child-care centers, showing that the concentrations follow a log-normal distribution. This coincides with the characteristics of indoor air radon concentration distributions reported in several previous studies (Nero et al., 1994; EC, 1996; Gundersen and Schumann, 1996), confirming that the radon concentration distribution in Korean child-care centers follows a log-normal distribution identical to that of other indoor radon concentrations.

The arithmetic and geometric means of radon concentrations in child-care centers are presented in Tables 3 and 4. The arithmetic mean of the radon concentration per measurement location was 52.3 ± 35.5 Bq m^{-3}, with arrange of 7.9–319.9 Bqm^{-3}. Additionally, the arithmetic mean of the radon concentration in child-care centers, calculated based on the mean of radon concentrations measured at two separate locations in a single child-care center, was 51.7 ± 32.3 Bqm^{-3}, with arrange of 11.2–222.5 Bqm^{-3}. The ratio of measured radon concentrations in excess of 148 Bqm^{-3}, which is the upper limit recommended by the South Korea's Indoor Air Quality Control in Public Use Facilities, etc. Act and the U.S. EPA was also examined in the target child-care centers in this research.

Table 5 shows the comparison of average radon concentrations per determining factor considered likely to affect the variations of indoor radon concentrations in child-care centers. The results indicate a statistically significant correlation between radon concentration levels and building type and area, the frequency of opening of windows, and the duration of ventilation, but not between radon concentration levels and year of construction, i.e., the deterioration of the building.

Table 6 shows the results of an analysis of covariance on whether the fluctuation of radon concentrations is correlated with the ventilation volume by setting the duration of the opening of windows as the indirect indicator of ventilation volume while controlling other influential factors to assess the effect of ventilation volume on the fluctuation of indoor radon concentrations. The indirectly determined ventilation volume shows a statistically significant correlation with the fluctuation of indoor radon concentrations, while controlling for the effects of construction year, indoor area, and the frequency of opening windows; the effect of the ventilation volume was than that of the other variables.

Table 1
Paired *t*-test data of radon concentrations (Bq·m^{-3}) in children's activity area obtained from duplicate detectors.

	N	Mean concentration	S.D.	p-value
detector 1	7	105	54	>0.05
detector 2	7	107	57	

Table 2
RDP (%) results of radon concentrations in children's activity area obtained from duplicate detectors.

	N	Mean	S.D.	Minimum	Maximum
RPD	7	8	6	2	16

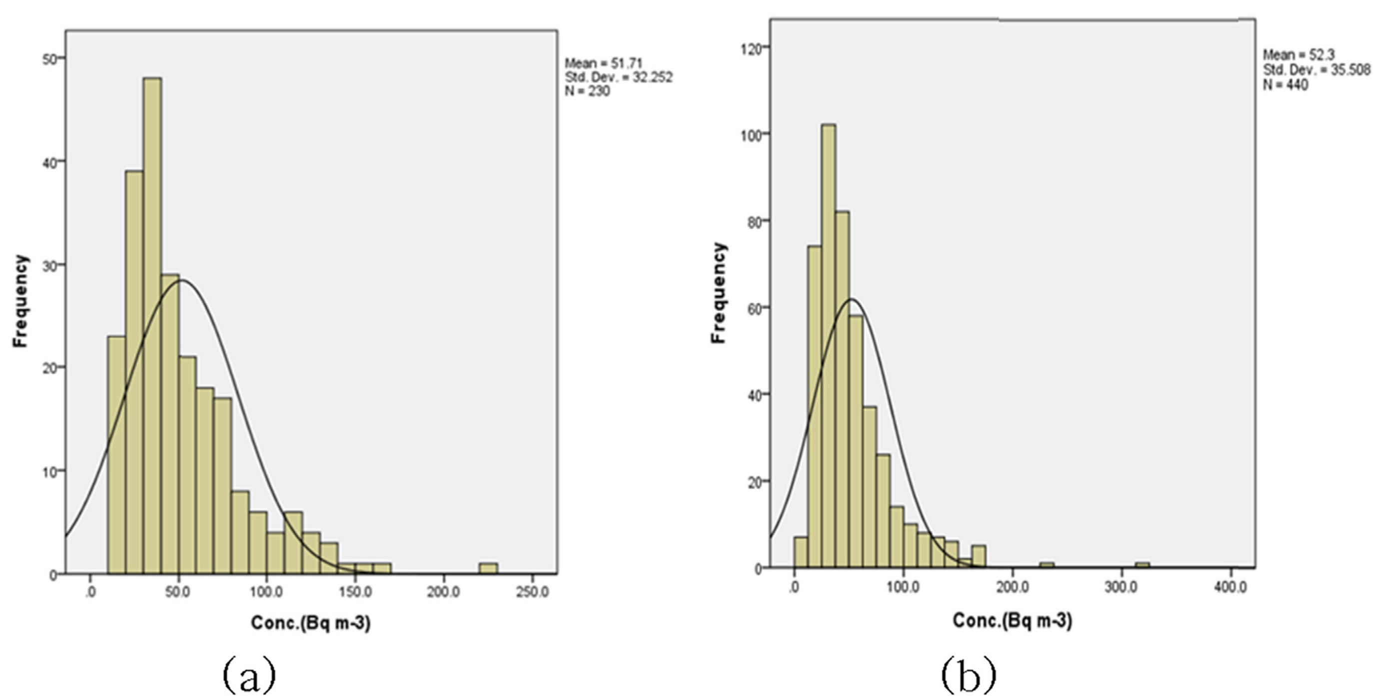

Fig. 1. Radon concentration distribution in indoor air of child-care centers.
(a) Mean concentration distribution per child-care center.
(b) Concentration distribution per measurement location.

Table 3
Radon concentration distribution in indoor air of child-care centers ($Bq \cdot m^{-3}$).

	N	Arithmetic mean	Arithmetic S.D.	Minimum	Maximum	Geometric mean
Measurement location	440	53	36	8	320	44
Child-care centers	230	52	320	11	223	44

Table 4
Excess rate of radon concentration above the recommended level for indoor air in child-care centers.

	N	Excess number	Excess	Description
Per location	440	11	2.5%	Excess number (rate) per measurement location
Facility mean	230	3	1.3%	Mean value per measurement locations (2) for each facility
Facility	230	10	4.3%	Considered as excess if either measurement is in excess

Table 5
Comparison of mean radon concentrations ($Bq \cdot m^{-3}$) per determining factor in child-care center.

Determining factor		N	Mean	S.D.	p-Value	Coefficient for post-hoc test
Building type	House	300	57	39	<0.05	
	Apartment	137	43	24		
Area (m^2)	Below 100	12	62	29	<0.05	a
	100–300	80	47	26		a,b
	300–600	29	31	13		b
	Above 600	8	38.1	17		b
Construction year	Prior to 1990	81	54	47	>0.05	
	1990–1999	161	50	32		
	Since 2000	164	52	31		
Frequency of open windows	Closed	4	113	50	<0.05	a
	Open once a day	62	49	25		b
	Open 2–4 times a day	273	54	38		b
	Open in daytime	92	50	33		b
	Other	5	24	7		b
Duration of ventilation	Below 30 min.	270	57	39	<0.05	a
	30 min to 1 h	113	45	29		a,b
	1–2 h	42	42	20		a,b
	2–3 h	8	34	8		b

Table 6
ANCOVA results of the effects of ventilation on radon concentration increments in child-care centers.

Source	Type III Sum of square	df	Mean square	F	Sig.	Partial eta squared
Corrected model	2.034	6	0.339	5.230	0.000	0.074
Intercept	34.015	1	34.015	524.929	0.000	0.574
Construction year	0.005	1	0.005	0.077	0.781	0.000
Indoor area	0.760	1	11.736	11.736	0.001	0.029
Frequency of Open window	0.322	1	4.970	4.970	0.026	0.013
Duration of open window	1.029	3	5.291	5.291	0.001	0.039
Error	25.271	390				
Total	1084.324	397				
Corrected total	27.305	396				

4. Discussion

The present study was conducted following the method used by the Ministry of Environment in the nationwide survey on the state of radon levels in houses. Our study provides fundamental data on the distribution of radon concentrations in child-care centers in South Korea, which can be utilized to establish radon mitigation strategies. A total of 235 child-care centers were randomly selected from the nation's child-care centers, and radon detectors were installed at two locations in each child-care center. Detectors from 230 child-care centers were collected for analysis. According to the data released by Statistics Korea in 2015, there are 43,742 child-care centers in South Korea, and the number of child-care centers selected for this research accounts for mere 0.5% of the total. Hence, the degree of representativeness of the results regarding indoor air radon concentrations in child-care centers across the country is very low. However, the present study is the first in South Korea to examine child-care centers following the method of the nationwide survey on the state of radon in houses. While studies on children's exposure to many chemicals present in indoor air have been conducted over the last several years, there has been no investigation on the radon levels in child-care centers. Therefore, this research is significant in that it provides a starting point for national-level studies on children's exposure to and protection against radon.

The distribution of indoor radon concentrations in Korean child-care centers follows a log-normal distribution as suggested in previous studies (Nero et al., 1994; EC, 1996; Gundersen and Schumann, 1996). This log-normal distribution can be explained through the following statistical considerations. If a parameter depends on the addition of multiple independent variables showing a distribution with similar variance, the measurement value of the parameter commonly tends to follow a normal distribution. In the case of radon inside buildings, there are a number of independent variables. However, their effect is multiplicative rather than additive. There is only one main source of indoor radon (soil) and its effect depends on the factors affecting the amount of radon penetrating a building and the rate at which it diffuses. If these elements are weighted and independent, the indoor radon concentration can be expressed by the following equation:

$$\mathbf{Rn}_{in} = \mathbf{Rn}_{out} + A \times B \times C, \tag{4}$$

where Rn_{in} is the indoor radon concentration, Rn_{out} is the outdoor radon concentration, and *A, B, C* … are the functions of variables such as radon concentration within soil, permeability of the ground, the number and size of inflow pathways, sound pressure of the building, and ventilation of the building. These variables determine how much radon is generated from the ground, how much radon enters the building, and how long it remains. The above equation can be re-written as follows.

$$\ln(\mathbf{Rn}_{in} - \mathbf{Rn}_{out}) = \ln(A) + \ln(B) + \ln(C) + \cdots \tag{5}$$

If there are terms of several independent variables in the above equation, the distribution of each term has a similar variance. Thus, ln ($Rn_{in} - Rn_{out}$) shows a log-normal distribution (Miles, 1998). Therefore, the log-normal distribution of radon concentrations suggests that the major source of radon in Korean child-care centers is soil, which is similar to other indoor environments, and that other determining factors are involved in the penetration of radon into buildings and its diffusion.

The average radon concentrations measured in Korean child-care centers per measurement location and per child-care center are both approximately 52 Bq m^{-3}, which is about one-third of the upper permitted limit of 148 Bqm^{-3} set by the South Korea's Indoor Air Quality Control in Public Use Facilities, etc. Act and the U.S. EPA. This level is about half the indoor air radon levels in dwellings (102 Bqm^{-3}) measured by the Ministry of Environment from December 2013 to February 2015, confirming that indoor radon concentrations in Korean child-care centers are lower than those of common residential dwellings. This is explained by the fact that child-care centers, compared to common residential dwellings, are designated as management target facilities for indoor air quality control set by the South Korea's Indoor Air Quality Control in Public Use Facilities, etc. Act of the Ministry of Environment, and have been constantly managed by law. This is also attributed to the actions child-care instructors are continuously taking to improve indoor air quality such as ventilation of indoor air, along with increased social awareness about the environmental health of children's activity spaces.

According to the survey results of environmental factors that are considered influential for variations in indoor radon concentrations and the analysis of their relevance to radon concentrations, the following result was derived. In terms of radon concentrations and building type, the single type child-care centers (including centers located in apartment units) have higher levels of radon concentrations than the multi-unit type child-care centers. The management of indoor air quality in home-based child-care centers located in an apartment unit typically depends on natural ventilation and not on a mechanical ventilation system. In addition, this study was conducted during the winter season so that the lack of natural ventilation seemingly led to an increase in indoor air radon concentrations. The results show a statistically significant dependency of radon concentrations on the size of the child-care centers. According to the post-hoc analysis, radon concentrations in child-care centers with an area smaller than 100 m^2 are higher than those in child-care centers with an area of 100 m^2 or larger. A smaller area implies a smaller indoor volume, and the indoor radon concentration probably increased due to a reduced capacity for indoor air radon to be diluted. Furthermore, most child-care centers with an area smaller than 100 m^2 are the ones run in apartment units, and as discussed earlier, the lack of ventilation in this type of child-care center leads to an increase in indoor radon concentration. The comparison between radon concentrations and year of construction shows no statistically significant difference. The year of construction is an indirect indicator of the deterioration of a building (cracks in walls etc.) and the indoor radon concentration was deemed to increase due to an increase in radon entering the building through such cracks. In this study, however, the year of construction and the indoor air radon concentrations were not significantly correlated, which may be attributed to constant repairs performed by building owners over time. It is well known that indoor radon levels are largely affected by indoor ventilation (Neuberger and Gesell, 2002; Lazar et al., 2003). The present study did not examine the amount of indoor ventilation in the targeted child-care centers. Instead, a correlation between indoor radon concentrations and indoor ventilation was inferred using the frequency of opening of windows as a variable. Radon concentrations vary significantly with the frequency of opening of windows. In particular, radon concentrations in child-care centers where the windows were not opened at all are higher than those in child-care centers where the windows were opened at least once a day. Similarly, a comparison between radon concentrations and the duration of the opening of windows (duration of ventilation) shows that child-care centers with the shortest duration of ventilation, less than 30 min, have higher radon concentration than those with ventilation times of 30 min or more. Hence, the correlation between radon concentrations and the frequency and duration of ventilation confirms that indoor radon concentrations in child-care centers are affected by ventilation.

An analysis of covariance was conducted to control interpretive errors in the variance analysis results, in which the variations in indoor radon concentrations may be attributed to the relationship between the influencing factors. This analysis was also carried out to identify the role of ventilation as a determining factor for the variation in indoor radon concentrations in child-care centers. The data confirmed that the duration of ventilation is the factor determining the fluctuation of indoor radon concentrations in child-care centers even if the effects of other influencing factors are controlled. This justifies the need to establish a plan for reducing radon concentrations in child-care centers through ventilation.

The US EPA (1994) recommends maintaining and managing the current environment if the radon concentration in children's activity space is 4 pCi L^{-1} (148 Bqm^{-3}) or lower and using ventilation if the radon concentration is 4–10 $pCiL^{-1}$ (148–370 Bqm^{-3}). The U.S. EPA also recommends an active reduction plan using active soil depressurization (ASD) for concentrations of 10 $pCiL^{-1}$ (370 Bqm^{-3}) or higher. In the present study, the concentrations per measurement location were 8–320 Bqm^{-3}, and the average concentrations in the child-care facilities were 11–223 Bqm^{-3}. Considering the recommendations of the U.S. EPA and that the amount of ventilation (duration of opening of windows) is the major determining factor for indoor radon concentrations in child-care centers in South Korea, we conclude that radon concentrations in Korean child-care centers should be reduced, maintained, and managed through appropriate ventilation to levels equal to or below 148 Bqm^{-3}, which is the maximum level recommended by the South Korea Ministry of Environment and the U.S. EPA.

5. Conclusions

To obtain data regarding the distribution of radon concentrations in child-care centers and to provide a foundation for the establishment of reduction and management strategies for radon in children's activity spaces, cumulative radon exposure concentrations were examined in 230 child-care centers nationwide from January to May 2015. We chose this period because radon concentrations show their highest indoor levels during winter and because the Ministry of Environment in South Korea has been conducting nationwide surveys of radon levels in houses for the past several years in wintertime as well. Thus, by employing the same radon sensors and the same sampling period, this study will enable future sharing of data with the national survey.

The average radon concentration in the targeted child-care centers was 51.7 ± 32.3 Bq m^{-3}, which about one-third of 148 Bqm^{-3}, which is the upper allowed limit set by South Korea's current Indoor Air Quality Control in Public Use Facilities, etc. Act and the U.S. EPA. Facilities with radon levels exceeding this upper limit accounted for 1.3% of the total. The amount of ventilation is strongly correlated with variations in indoor radon concentrations in child-care centers of South Korea. Therefore, it is desirable to place an emphasis on ventilation when establishing future plans of radon mitigation and management in child-care facilities.

The target child-care centers selected for this study account for only 0.5% of the total number of child-care centers in South Korea, thereby rendering the results of indoor air radon concentrations in child-care centers nationwide statistically deficient due to a low degree of representation. Nevertheless, the present study is the first to examine child-care centers in South Korea following the same method that was utilized in the nationwide survey of radon levels in houses. Numerous studies conducted in the past several years have investigated children's health with regard to many chemicals found in indoor air, but no study has examined the state of radon concentrations in child-care facilities. In this regard, this study provides a starting point for future research on environmental health at the national level and contributes to the protection of children's health against radon exposure in their activity spaces.

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