

Meta-analysis Study on Microenvironmental Characteristics of Radon Concentration in Korea

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ABSTRACT

Objective: The present study analyzed domestic and overseas academic journals to understand the research status and characteristics of radon concentration distribution in Korea in accordance with environmental conditions.

Methods: As part of the meta-analysis, pooled average concentration was calculated using an inverse variance-weighted average of the arithmetic means and standard deviations among the investigated values. Using the obtained pooled average concentration, a Monte-Carlo simulation was performed to increase the reliability of the occurrence possibility of the calculated concentration distribution. A total of 38 research articles were selected, including 27 articles published in domestic academic journals and 11 articles published in foreign academic journals.

Results: The comparison results showed differences in radon concentration distribution in accordance with regional and topographical characteristics.

Conclusion: Currently, even though research into radon is steadily picking up the pace in Korea much remains to be done. Additional research is thus needed to establish a baseline for radon emissions in Korea.

Key words: ²²²Rn, Monte-Carlo simulation, radon, meta-analysis

I. Introduction

Radon (²²²Rn) is the most potential and harmful radioisotope among the radon isotopes.¹⁾ It arises from soil and seeps into residential environments through concrete floors and wall cracks, holes in the floor, drain age pumps, connections between buildings, and small gaps or openings in hollow block walls. It is known that radon concentrations could sometimes reach levels harmful to public health if the gas flowing into a closed room is concentrated enough.²⁾

Generally, the concentration of radon in outside

air is very low but it can increase to high levels due to accumulation of radon gas in closed spaces. The freezing point of radon is below minus 68°C, and above this temperature, the element turns into gas. Because of its colorless and odorless properties in the gaseous state, radon is undetectable by human senses even in closed indoor spaces. Moreover, radon is a radioactive gas, which decays into radioactive elements such as ²¹⁸Po or ²¹⁴Po that emit alpha rays. These rays could cause serious damage to alveoli present in the lungs.^{3,4)}

Recent studies on people exposed to radon⁵⁻⁷⁾ showed that radon exposure at home and work is

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a serious health risk, and people exposed to high concentrations of radon for extended periods of time have increased risks of eventually developing lung cancers due to the pathological effects and functional changes in the respiratory system. It was reported that this risk depends on the indoor concentration of radon, duration of exposure, and degree of ventilation⁸⁻¹¹⁾. As such, radon is mainly emitted from soil and rock. Building materials are also known to be a major potential source of radon in the indoor environment.^{4,7,12-15)}

Even though the public's concern about radon is increasing since a domestic broadcasting company started raising awareness about radon exposure and health risks via a special program in 2014, correct information on the distribution characteristics of radon concentrations and risk-related information is not sufficient due to the lack of relevant data and research in the Korean context.¹³⁾ Accordingly, the Korean Ministry of Environment started a four-year R&D program with the purpose of collecting risk-related information on radon and developing relevant and suitable communication techniques and a radiation hazard index.¹³⁾

The present study collects and presents the research findings published in domestic and foreign academic journals as a part of an effort to understand the current situation on radon research in Korea as well as the distribution characteristics of radon concentrations in various environments.

II. Materials and Methods

1. Data collection

In order to collect the necessary information on domestic radon concentrations, relevant research papers were selected via a literature review and specific selection criteria using an electronic journal search. Additional research articles corresponding to the contents of the present study were short listed from the reference lists of the previously selected research papers.

The words used for the literature search included the following: 'radon', 'natural radiation', 'indoor environment', 'atmosphere', 'underground water', 'construction materials', and 'soil'. Words relating to environmental media, namely, 'air', 'water', and 'soil' were also used. The literature selection was limited to the Korean context, and only research articles published in related domestic and foreign academic journals, excluding presentations and reports at academic conferences, were selected. Thus, the resulting identified articles referred to investigations of radon under a domestic environment.

A total of 38 research articles were selected, including 27 articles published in domestic academic journals and 11 articles published in foreign academic journals. The findings of these research articles helped in the identification of trends in radon research in Korea, and the distribution characteristics of radon concentrations under various conditions were then reviewed.

2. Data analysis

The collected data were used to review trends in radon concentration studies in Korea in terms of the year of investigation and the media. The types of investigation methods were also examined, and the distribution characteristics of radon concentrations according to various conditions, such as regions, seasons, construction materials, and soil (rock) media were identified. Then, pooled average concentrations were presented as the inverse variance-weighted average as a result of meta-analysis for the arithmetic means and standard deviations among the investigated values using R statistics program. A Monte-Carlo simulation was performed using the calculated pooled average concentration. This simulation was performed to understand the reliability of occurrence possibility of the calculated concentration distributions, wherein the possibility of occurrence was confirmed if thrice the standard deviation of the concentration range exceeded 99%.

The inverse variance-weighted average method,

which helps analyze effect–magnitude measures, is a method for calculating pooled averages from average concentrations. These concentrations were sourced from the selected studies, with due consideration given to the size of each study such as the extent of data.²³⁾ The method assumes an approximately normal distribution of the estimated quantity of the pooled averages.

That is,

$$\bar{\theta}_i = N(\theta_i, \omega_i^{-1}), i = 1, 2, \dots, k$$

Here, ω_i is the inverse variance of $\bar{\theta}_i$, that is, $\omega_i = \frac{1}{var(\bar{\theta}_i)}$. In addition, k denotes the number of studies and is independent. Therefore, if the estimated quantity of the pooled averages is assumed to be $\theta_1 = \theta_2 = \dots = \theta_k = \theta$, the distribution approximates the normal distribution as follows.

$$\sum \bar{\theta}_i \omega_i \sim N(\theta \sum \omega_i, \sum \omega_i)$$

Therefore, the relevant equations are

$$\bar{\theta} = \frac{\sum_{i=1}^k \bar{\theta}_i \omega_i}{\sum_{i=1}^k \omega_i}$$

and

$$var(\bar{\theta}) = \frac{1}{\sum_{i=1}^k \omega_i}$$

Assuming an asymptotic normal distribution of $\bar{\theta}_i$, the 95% confidence interval of $\bar{\theta}_i$ was obtained using the equation below.

$$\bar{\theta} \pm 1.96 \sqrt{\frac{1}{\sum_{i=1}^k \omega_i}}$$

Here, ω_i acts as a weight in the pooling results, similar to many studies.

III. Results

1. Radon-related research in Korea

Figure 1 presents a sorting of the selected studies based on the year the field survey was conducted

in. This arrangement helps analyze the trends in research on radon with regard to various situations. If the field survey was continued in the following year, the beginning year was used as a marker. If it was carried out over multiple years, each year was sorted and considered separately. If the year of the survey was not noted in the study, its submission date was used to sort it accordingly.

The first domestic study on radon was carried out by the previous study,¹⁶⁾ who measured radon concentrations in soil by installing radon cups at a depth of 50 cm below the ground at four locations in Jeju city from May 1987 to April 1988. The first surveys of radon concentration in indoor air were conducted by the previous study,¹⁸⁾ who surveyed indoor air radon concentrations in 34 houses with basements, general underground shopping arcades, subways, underground passages, and underground parking lots from February 1988 to January 1989. This study surveyed radon indoor air concentrations for four locations (Seoul, Gunsan, Songtan, and Dogo) from December 1988 to April 1989. It was found that research on radon in Korea started in 1987 and continued until 1990, but no findings were reported from 1991 to 1994. Thereafter, studies on this topic continued from 1995 to 2014. These studies were most actively carried out in 1999, when as many as seven studies were published.

Table 1 sorts and presents the selected studies in

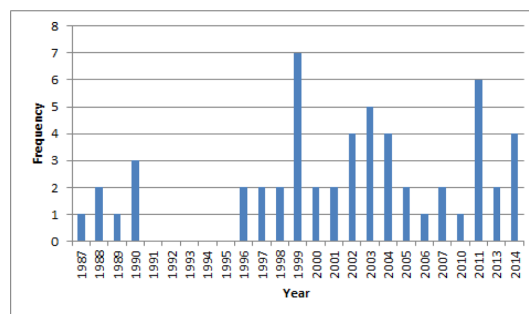


Fig. 1. Trends showing number of studies on radon in various environments in Korea by year

Table 1. Trends showing annual research on radon conducted in accordance with the media and survey purposes (unit: number of studies)

Classification	Before 1990	1990-1994	1995-1999	2000-2004	2005-2009	After 2010	Total
Indoor air	3	2	6	7	2	4	24
Outdoor air			2	5	1	1	9
Underground water				1	2	3	6
Soil	1		1			1	3
Construction material		1				3	4
Radon reduction						1	1

terms of the media surveyed or the purpose of the survey (outdoor air, indoor air, soil, underground water, construction material, and radon reduction efficiency). It presents the trends in research on radon in Korea every five years. If the field survey was carried over to the following year, the results of the study that stretched over a longer period were retained. If the study covered multiple years, it was sorted in terms of each year in question. If the survey year was not identified in the research paper, the year of the study's publication was used to sort the study (as explained previously).

The present study classified domestic radon-related surveys into indoor air radon concentration surveys, outdoor air (atmospheric) radon concentration surveys, underground water radon concentration surveys, and radon emissions from soil and construction materials. Only one survey addressed reduction in radon concentration after construction.¹⁹⁾ It was found that many indoor air radon concentration surveys have been steadily carried out from the beginning of the study period to the present year, whereas indoor air radon concentration surveys and underground water radon concentration surveys have been consistently performed after 1995 and 2000, respectively. Only a total of three soil radon concentration surveys were identified, one before 1990, one between 1995 and 1999, and one after 2010.

Most of these studies could have been spurred by the findings of previous work on radon in the environment, namely those that confirmed that radon

was a cause of lung cancer among uranium mine workers and that exposure to radon in closed indoor spaces and increase of radon exposure time raised the possibility of lung cancer occurrence.^{3,5-7,11,20-22)}

In addition, radon is emitted from soil and is reported to be introduced indoors through cracks in building flooring (85-90%), construction materials (2-5%), and underground water (1% or less).³⁾ Radon is also known to dissolve and accumulate in water from underground sources.^{4,7,15,23-26)} The importance of radon sources has also been recognized in Korea. Thus, radon concentration surveys in the underground water of subway stations have been carried out as part of air quality management, with many surveys of underground water and building materials having been conducted since 2000 from the perspective of collating baseline data to determine the sources of the gas and to establish radon management plans.

2. Characteristics of radon concentration distribution in indoor environments

The present study was carried out in 2014 to secure basic data on the dangers of radon exposure, and developing communication methods and a hazard index over the next four years. To evaluate the effect of radon exposure on health, the data were reanalyzed using the findings of only those studies that investigated radon concentrations with an alpha track detector. This was done in the interests of attaining reliable results, by utilizing long-term rather than short-term measurements.

As part of the effort to calculate radon concentrations inside residences nationwide, the pooled average concentration of radon was calculated using survey data from houses located in the metropolitan cities of Seoul, Busan, Daegu, Gwangju, Daejeon, and Incheon and nine Korean provinces (Table 2). The pooled average indoor air concentration of radon within a residence was found to be 57.7 ± 5.8 Bq/m³, which does not exceed the recommended criterion for radon in the air of multi-purpose facilities as per the Indoor Air Quality Management Act of the Ministry of Environment, Korea. Moreover, this value is lower than half the recommended radon level in indoor residential air as per the stipulations of the United States Environmental Protection Agency (148 Bq/m³). The highest concentration of radon among the metropolitan cities was found in Seoul (76.2 ± 20.1 Bq/m³), and the highest concentration of radon among the provinces was found in Jeollabuk-do (90.2 ± 30.5 Bq/m³). Fig. 2 shows possible distributions of radon concentrations inside res-

idences located in six metropolitan cities and nine provinces, and calculated using a Monte-Carlo simulation. The results show differences in the possible distribution of radon concentrations among cities. A comparison across six metropolitan cities indicates that Seoul and Chungcheongbuk-do have higher radon concentrations compared to other cities and provinces, respectively. Chungcheongbuk-do has high uranium content, and uranium is the mother nuclide of radon. Given the area's topographic characteristics, it was home to many uranium mines, and thus shows higher radon concentration distribution compared to the other provinces. The data from these studies also showed that radon concentrations vary considerably within residences. Indeed, Lee *et al.* (2012) found similar results and observed that radon concentrations within residences are affected by regional and topographical characteristics.²⁴⁾

A comparison of radon concentrations in indoor air by building usage showed higher concentrations in offices and subways compared to stores and hos-

Table 2. Comparison of pooled average concentrations of radon in indoor residential air in metropolitan cities (unit: Bq/m³)

Major metropolitan cities	Number of studies	Pooled average concentration	95% confidence interval	References
Seoul	7	76.2±20.1	36.8-115.6	
Busan	2	38.0±15.6	7.4-68.7	
Daegu	2	43.0±17.8	8.1-77.9	
Gwangju	2	57.2±17.8	22.3-92.1	
Daejeon	2	52.8±25.3	3.3-102.4	Chang et al. (1991) ³⁾
Incheon	2	39.8±18.5	3.6-76.0	Chung et al. (2001) ⁷⁾
Gyeonggi-do	3	68.7±28.2	13.4-124.0	Kim et al. (2002) ¹⁸⁾
Jeollabuk-do	3	90.2±30.5	30.5-150.0	Kim et al. (2005) ¹⁹⁾
Jeollanam-do	3	76.6±23.9	29.7-123.4	Kim et al. (2011) ¹⁷⁾
Gyeongsangbuk-do	13	66.9±15.0	37.5-96.3	Kim Y. S. (1990) ¹⁵⁾
Gyeongsangnam-do	3	50.6±23.5	4.61-96.6	Kim Y. S. (1991) ¹⁶⁾
Kangwon-do	2	77.7±48.3	ND-172.3	Lee et al. (2006) ²⁶⁾
Chungcheongbuk-do	2	87.7±103.9	ND-291.3	Lee et al. (2015) ²⁵⁾
Chungcheongnam-do	3	89.6±37.5	16.2-163.0	
Jeju	2	56.5±34.0	ND-123.1	
Nationwide	51	57.7±5.8	46.3-69.0	

ND: Not detected

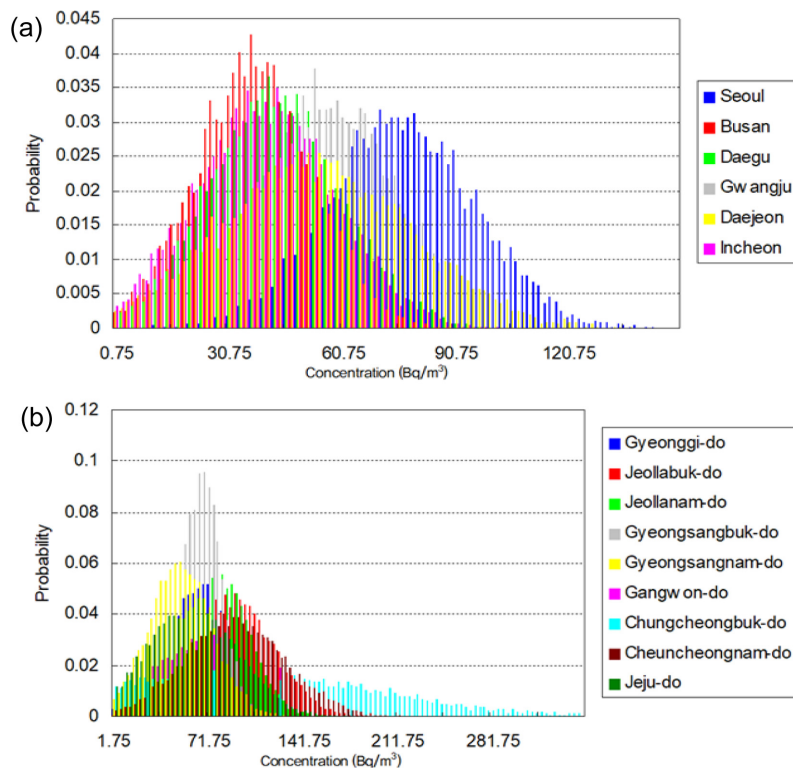


Fig. 2. Calculated probabilities of the distributions of radon concentrations in indoor residential air for (a) six major metropolitan cities and (b) nine provinces in Korea

pitals, but this difference was not large (Table 3). To compare the distribution of radon concentrations by building usage, the possibility of the presence of radon in indoor air by building usage was calculated using a Monte-Carlo simulation. These results showed that the distribution of radon in offices was typically higher than that in other (non-office) buildings. This may be due to insufficient ventilation than other building usages. In the case of subway stations, the fluctuation in radon concentrations was found to be lower than in the case of other building usages. In such cases, the low fluctuation in radon concentrations may be due to fewer environmental changes within each facility on account of controlled heating and air conditioning equipment. The difference in radon concentration within each subway station may be attributed to environmental factors such as differences in geography and the depth

at which the station is located.

Figure 3 shows the results of a comparison of radon concentrations in underground and above-ground spaces.²⁸⁻³¹⁾ Note that the under- and above-ground spaces of apartments were excluded from this analysis as it was determined that inclusion of these spaces may confound the data analysis; in the case of apartments, the differentiation between under- and above-ground spaces is not clear, and given the current structure of the apartments, there is no living area in underground spaces.

The radon concentration in underground spaces was found to be higher than that of above-ground spaces; the pooled average concentration of radon in 16 underground spaces was 34.8 ± 3.8 Bq/m³, and the corresponding value for 16 above-ground spaces was 32.5 ± 3.0 Bq/m³. The distribution of radon concentrations was also found to be higher in under-

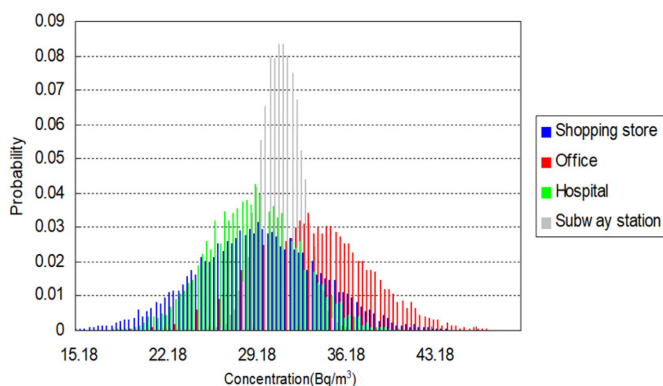


Fig. 3. Calculated probabilities of the distributions of radon concentrations according to building usage

Table 3. Comparison of pooled average concentrations of radon in indoor air according to building usage (unit: Bq/m³)

Building type	Number of studies	Pooled average concentration	95% confidence interval	References
Shopping store	4	29.8±4.9	20.2-39.3	Jeon and Kim (2006) ¹⁰⁾
Office	4	33.4±4.5	24.5-42.3	Jeon et al. (2007) ¹¹⁾
Hospital	4	29.1±3.6	22.0-36.1	Kim et al. (2002) ¹⁸⁾
Subway station	7	31.1±1.6	28.0-34.3	Lee et al. (2006) ²⁶⁾ Yoon et al. (2010) ³⁹⁾

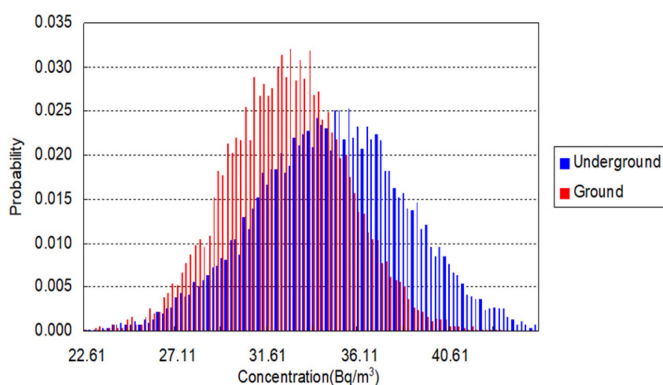


Fig. 4. Calculated probabilities of the distributions of radon concentrations in underground and above-ground spaces

ground spaces, as shown in Fig. 4. This result is in agreement with that of an existing study³²⁾ which explained that radon is emitted from soil and the insufficient ventilation of the air near soil causes radon concentrations to be higher in underground spaces. Our study also confirms that the radon concentration in underground spaces exceeds that in above-ground spaces.

Residence types in Korea are diverse compared to

other countries. Accordingly, in the present study, the types of residences in previous work were classified into traditional housing, modern housing, and apartments, and the radon concentrations in the living spaces of each residence type were recorded.³³⁻³⁵⁾ Then, the pooled average concentration was calculated.

For traditional housing, reanalysis of the data obtained from two studies showed radon concentra-

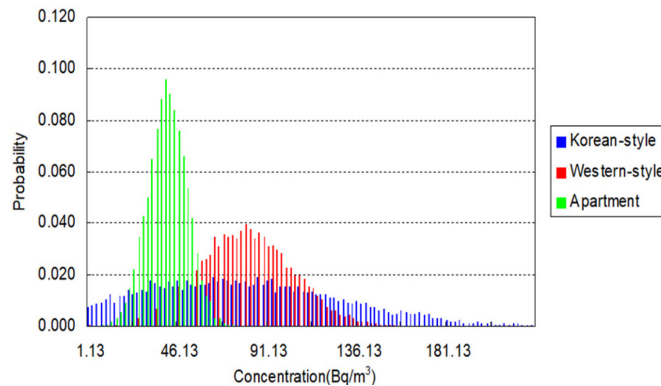


Fig. 5. Calculated probabilities of the distributions of radon concentrations according to residence types

tions of 70.6 ± 57.4 Bq/m³. The corresponding values for modern housing and apartments were 79.0 ± 24.4 Bq/m³ and 40.1 ± 9.8 Bq/m³ (from three studies each). Apartments showed the lowest pooled average concentration, whereas traditional housing showed pooled average concentrations lower than those of modern housing. The result indicates that, in the case of apartments, the radon emitted from soil seeps indoors to a less extent compared to other types of housing. The results of the comparison of the distributions of pooled average concentrations of radon for traditional and modern housing showed that while the former has a wide concentration distribution, modern housing is characterized by a narrower distribution compared to traditional housing. On the other hand, the average radon concentration is higher in modern housing than traditional housing (Fig. 5). This may be governed by the ventilation conditions depending on the building structure; in the case of traditional housing, they contribute significantly to the indoor radon concentrations compared to modern housing.

IV. Discussion

Recently, social interest in radon emissions in the indoor air environment has increased. Radon is mainly emitted by the soil and rock in building construction, and these emissions also add to radon

concentrations in indoor environments. It is known that people exposed to high concentrations of radon for an extended period of time could possibly develop lung cancer. Accordingly, active research on indoor radon is needed, and it is necessary to arrive at a baseline to be able to conduct relevant research in the future. On the other hand, research on radon is insufficient in the Korean context. Accordingly, the Ministry of Environment started research with the purpose of collecting information related to the danger of radon, and to develop communication methods and a suitable hazard index. To understand current status of radon-related research in Korea as well as the distribution characteristics of radon concentrations in terms of environmental conditions, the findings of domestic and foreign academic journals were analyzed.

Material for this study was collected from electronic journals via a literature reviews and research articles matching the content of the present study were selected.

Specific terms words were used in literature search, which focused on investigations in domestic environments. A total of 38 research articles were selected (27 articles published in domestic academic journals and 11 in foreign academic journals). The trends of radon-related research in Korea and the characteristics of radon concentration distributions under various conditions were then investigated in

terms of the year of the investigation and environmental media.

In addition, to probabilistically present the characteristics of radon concentration distributions, pooled average concentrations were calculated using inverse variance-weighted averages as part of the meta-analysis of the arithmetic means and standard deviations among the investigated values. The obtained pooled average concentrations were fed into a Monte-Carlo simulation to increase the reliability of the occurrence possibility of the calculated concentration distributions.

Radon-related domestic surveys were classified into those measuring the amount of radon emitted in indoor, outdoor, underground water, and soil environments as well as by construction materials. The first domestic radon-related research was carried out by Kang and Kim,¹⁷⁾ who measured radon concentrations in soil by installing radon cups. Later, Kim *et al.*²⁸⁾ carried out the first survey of radon concentrations in indoor air at four locations in Korea. These studies likely focused on radon concentrations in closed spaces given previous reports of the relationship between lung cancer in uranium mine workers and radon. With regard to the source of radon in indoor spaces, the highest proportion is reported to have been emitted from soil through gaps in building flooring (85-90%), followed by the radon emitted from construction materials (2-5%) and underground water (1% or less).^{3,36)}

The present study helped clarify the status of research on radon in Korea as well as the distribution characteristics of radon concentrations under various conditions. Currently, even though research into radon is steadily picking up the pace in Korea much remains to be done. Additional research is thus needed to establish a baseline for radon emissions in Korea, and its results would be helpful to establish radon reduction policy.

V. Conclusions

To evaluate the effect of radon exposure on health, this study used data from long-term measurements effected with an alpha track detector so as to produce reliable results. The pooled averages of indoor residential radon concentrations were highest in Seoul and Jeollabuk-do among large domestic metropolitan cities and nine provinces (76.2 ± 20.1 and 90.2 ± 30.5 Bq/m³, respectively).

As a result of Monte-Carlo simulation for possible distributions of radon concentrations had differences existed in the distributions of radon concentrations because of regional and topographical characteristics. Distributions of radon concentrations according to building usage were compared using Monte-Carlo simulation, and showed that the radon concentration in offices (where ventilation may be insufficient) was more or less high than that of buildings with other usages.

Radon concentrations were also compared between the underground and aboveground cases. As the differentiation between the aboveground and underground spaces in apartments is ambiguous, and because most underground spaces of apartments do not serve as living spaces, apartments were excluded from the analysis. The radon concentration in underground spaces was higher than that of aboveground spaces. This result can be attributed to the fact that the major source of radon is soil, and underground spaces are thus obviously influenced to a greater extent by radon concentration.

A comparison of radon concentration by residence types (traditional housing, modern housing, and apartments) indicated that apartments had the lowest radon pooled average density (40.1 ± 9.8 Bq/m³). The distributions of the pooled average concentrations of radon showed that modern housing has a narrower distribution compared to traditional housing. In the

case of apartments, the amount of radon seeping from soil in to the indoor environment was small, while modern housing was found to be less affected by the ventilation conditions due to the building structure compared to traditional housing.

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