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Occupational exposure monitoring for radon in various manufacturing workplaces and underground public-use facilities in Korea

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In this study, we measured the levels of occupational radon using short-term (electret passive environmental radon monitor system [E-PERM®]), long-term (Radtrak2® alpha track), and real-time (RAD7) monitoring detectors and characterized radon exposure levels in workplaces directly handling radon raw materials and byproducts and underground public-use facilities likely to be exposed to radon in the form of a naturally occurring radioactive material (NORM). The geometric means (GMs) of occupational radon exposures measured at 10 manufacturing workplaces and 11 underground public-use facilities were 86.4 Bq m^{-3} (n = 299) overall, 60.7 Bq m^{-3} (n = 91) for short-term measurements, 132.4 Bq m^{-3} (n = 176) for long-term measurements, and 30.0 Bq m^{-3} (n = 32) for real-time measurements. More importantly, the GM of radon levels measured at the underground facilities [118.9 Bq m^{-3} (n = 127)] was significantly higher than that found at the workplaces [68.3 Bq m^{-3} (n = 172)] (p < 0.001). We found that workers at underground public-use facilities could be unintentionally exposed to higher radon levels resulting from NORMs. Therefore, we suggest that the Korean Occupational Safety and Health Act strengthens the regulations related to occupational exposure management for radiation and radon and establishes a more comprehensive control system to regularly monitor, manage, and reduce the levels of occupational radon exposure, particularly NORMs. In doing so, we can protect workers' health and safety from potential radon exposure at various workplaces and underground public-use facilities. Further studies should be conducted to quantitatively evaluate occupational radon exposures for a larger number of other underground facilities and workplaces, build radon-specific job or task-based exposure matrices, and follow-up health effects for workers who could possibly be exposed to radon or NORMs.

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Environmental significance

High levels of radon were recently detected from bed mattresses with monazite, a raw material of household products. Concerns about indoor radon exposure for the general population in residential housings as well as occupational exposure at workplaces where workers directly handle radon-containing raw materials and process byproducts have increased in Korea. However, many previous studies on radon exposure assessment and impacts on their health effects mainly focused on residential dwellings, subway stations, and daily household products. Due to this reason, detailed information and quantitative data on occupational radon exposure at various workplaces and underground public-use facilities were not fully demonstrated and are still limited. We measured, evaluated, and compared the levels of occupational radon exposure at underground public-use facilities likely to be exposed to radon in the form of naturally occurring radioactive materials (NORMs) and various workplaces handling radon-containing raw materials using short-term, long-term, and real-time radon monitoring detectors. We found that the levels of occupational radon exposure were significantly higher at the underground facilities than at the workplaces. Thus, our study findings indicate that comprehensive exposure management and activities under the related laws and regulations are strongly required to regularly monitor, evaluate, and reduce the levels of occupational radon exposure not only in workplaces but also at the underground public-use facilities to protect workers' health and safety from potential radon exposure in the future.

1. Introduction

Radon (^{222}Rn) is a colourless, odourless, inert gas-type radioisotope formed naturally by the decay of uranium and thorium. Radon exists in natural environments, such as air, rock, water, and soil, and emits alpha particles that can cause cancer, as a natural radioactive element and does not react chemically with other substances.[1–3] Radon, existing anywhere in our daily

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living environment, can stick to dust and travel into air. Radon is 7.5-fold heavier than air, so it flows mainly through the surface floors or cracks in the walls of building basements.[4,5] Most importantly, radon in soil can travel to near-field areas by diffusion and is likely to impact the respiratory tract of workers because it can move vertically through underground holes and building exhausts. It is also known that older buildings generally have higher risks of exposure to high levels of radon.[6,7]

In 2018, public concerns increased as broadcast news reported that high levels of radon were detected in monazite, a raw material that releases negative ions from bed mattresses and beddings in Korea.[8,9] In particular, the effective doses of radon and thoron for various household products, including beds and mattresses that release radon, were shown to exceed 1 mSv per year.[10] Therefore, to protect worker health and safety, the Ministry of Employment and Labour (MoEL) conducted a comprehensive survey on the working environment (including exposure assessment) for workers at some workplaces that directly handle monazite among mattress manufacturers nationwide.[11]

The World Health Organization (WHO) International Agency for Research on Cancer (IARC) classified radon as a Group I carcinogen.[12] Several studies, including exposure assessment, risk assessment, and epidemiological studies, have reported that radon exposure has a significantly positive association with an increased incidence and mortality of lung cancer.[13–17] However, some recent studies showed that the risk of lung cancer could be significantly elevated by not only radon but also other nonoccupational factors. Two studies reported the possibility of a joint effect of smoking and radon exposure,[18–20] and another study also demonstrated that the risk of lung cancer mortality was significantly associated with nonoccupational factors, including nationality, region, education, and smoking history, rather than radon exposure.[21]

Other studies that have observed the long-term health effects of occupational radon exposure among workers in various industries, including uranium miners, have also reported significantly positive associations with lung cancer, but evidence on risks of other types of cancers and chronic diseases (*e.g.*, skin cancer, stomach cancer, kidney cancer, leukaemias and non-Hodgkin lymphoma, cardiovascular diseases, *etc.*) remains limited.[22–28]

Considering the health effects of radon exposure, many domestic experts in the fields of environmental health and industrial hygiene conducted several studies of occupational exposure assessment at various workplaces, such as building material manufacturing sites and offices,[29] fertilizer, gypsum board and cement manufacturing sites,[30] sites that employ manufacturing processes using monazite,[11] and Seoul and other metropolitan subway stations.[31–34] Based on the study results, these studies have tried to understand the current status and characteristics of occupational radon exposure and develop more effective preventive measures for reducing the radon exposure levels at workplaces exceeding the occupational exposure limits (OELs).

Western countries have established and managed strict reference levels (recommended) for radon exposure to humans. First, the WHO suggested that a reference level of 100 Bq m^{-3} not be exceeded,[1] and the International Commission on Radiological Protection (ICRP) also set a reference level of 300 Bq m^{-3}.[3] The U.S. Environmental Protection Agency (EPA) set a derived reference level of 148 Bq m^{-3} in residential dwellings.[35] According to the Indoor Air Quality Control Act, the Korean Ministry of Environment (MoE) similarly established an advisory reference level of 148 Bq m^{-3} in multiple public-use facilities.[36,37] On the other hand, most European countries (*e.g.*, U.K., France, Italy, Denmark, Switzerland, *etc.*) set the reference levels for indoor radon exposure at residential housing in the range from 148 to 400 Bq m^{-3} except for some countries, including Latvia, Slovenia, and Slovakia, which set an advisory level as 1000 Bq m^{-3}.[38] Japan set a higher reference level of 600 Bq m^{-3}.[39,40] In 2013, the MoEL approved lung cancer caused by occupational exposure to radon or radioactive materials (when exposed to underground workplaces with poor ventilation) as one of the work-related diseases in Korea.[41] In 2018, the MoEL also established an OEL for radon of 600 Bq m^{-3} with revision of the MoEL's Notice No. 2018-24, "Occupational Exposure Limit Values for Chemicals and Physical Agents".[42]

However, radon was not included as one of the hazardous risk factors required to assess the level of worker exposure under the Korean Occupational Safety and Health Act; thus, there has been no compulsory obligation or responsibility to regularly measure, evaluate, and manage the radon exposure levels at workplaces to date. Furthermore, most previous studies mainly focused on various sites or products that are expected to have high levels of radon exposure and health effects, such as residential housings, daily household products, bed mattress manufacturing workplaces using monazite as raw materials, and subway stations in metropolitan cities in Korea. Thus, the fundamental information on the level of short- and long-term radon exposure data for workers is not fully demonstrated and remains limited in the manufacturing workplaces and underground public facilities.

Therefore, the purpose of this study is to monitor radon exposure levels using short-term, long-term, and real-time monitoring devices as well as to characterize occupational radon exposure in various manufacturing workplaces (where either radon raw materials or related process byproducts are directly used) and underground public-use facilities (where radon is likely to be exposed in the form of naturally occurring radioactive materials, hereinafter NORMs). Ultimately, we aim to provide sufficient evidence on the quantitative radon exposure datasets at workplaces and underground facilities to reduce occupational radon exposure potential for workers and establish preventive measures on sites.

2. Materials and methods

2.1 Selection of study subjects

2.1.1 Manufacturing workplaces. We collected information on a total of 66 manufacturing companies nationwide that directly handle monazite powder obtained from a survey report on the working environment conducted by MoEL. We reviewed the collected information and additional survey results and classified them into simple distributors ($n = 32$) and manufacturers ($n = 34$) that directly use radon raw materials and process byproducts. After excluding simple distributors, we included only manufacturers that directly use raw materials and byproducts in this study.

Most importantly, a manufacturing company that handles phosphate scale process byproducts with potassium chloride and another company that directly handles potassium chloride and phosphate raw materials were included. The companies ($n = 22$) that have already conducted radon exposure monitoring in other previous studies, that are in the process of abolishing business registrants, or that use a small amount of less than 1 ton per year were excluded. We included some companies that combine simple distribution and manufacturing, but two companies classified as manufacturers exporting raw materials overseas immediately after purchasing them and one company (not manufacturing but simple distribution) were also excluded.

We requested that the selected candidate companies cooperate in on-site radon measurement, but several companies rejected the measurement for various reasons. Therefore, a total of only 10 manufacturing workplaces were finally selected as the subjects of this study.

2.1.2 Underground public-use facilities. In this study, the authors measured the radon concentrations in air at underground public-use facilities located in large metropolitan cities to compare and evaluate radon exposure levels from NORMs that are widely present in indoor public-use facilities and working environments. In particular, a number of previous studies have evaluated radon exposure levels in subway stations and facilities in metropolitan cities in Korea.[31–33,43,44] Thus, after excluding subway stations and facilities in this study, underground public-use facilities such as underground public areas, tunnels, parking lots, underground spaces in residential and commercial buildings, and offices were selected as study subjects. Due to ongoing repair and construction on sites, some facilities were also excluded from this study. Therefore, 11 underground public-use facilities capable of measuring radon on site were finally selected for this study.

2.2 Occupational exposure assessment

We visited 10 dometic manufacturing workplaces (A1 to A10) and 11 underground public-use facilities (B1 to B11) selected for this study and measured radon exposure concentrations in air using short-term, long-term, and real-time monitoring devices for approximately 3 months from June to October 2019. Indoor radon measurement in air was performed according to the alpha track detection method using the same monitoring devices used in the previous study. For long-term radon monitoring (>2 months), Radtrak2® alpha track detectors (Radon Environmental Management Corp., Maple Ridge, BC, Canada) were used,[45,46] and electret passive environmental radon monitor (E-PERM®) detectors (Rad Elec Inc., Frederick, MD, USA) were used for short-term monitoring (<7 days).[47,48] An active-type RAD7 radon detector (Durridge Company Inc., Billerica, MA, USA) was used for the real-time monitoring of radon concentrations per hour. The RAD7 radon detector, which was previously used in several studies, can measure real-time radon concentrations using a method of collecting alpha particle emissions by analysing the detector's internal spectrum using static electricity.[11,43,49,50]

Prior to occupational radon monitoring, we sent three radon detectors (E-PERM®, Radtrak2®, RAD7) to the professional laboratory accredited by MoE and received a certificate of calibration from the laboratory. Then all radon detectors were also tested and approved by a national institution, which performs quality assurance (QA) testing for accuracy, precision, and reliability of the detectors according to the Korean indoor air quality testing methods and standards. The radon concentrations at the workplaces were continuously measured for 8 consecutive hours in consideration of the daily working hours for workers. The short-term measurements using E-PERM® detectors were performed for at least 7 days, but the long-term measurements using Radtrak2® alpha track detectors were collected for 20–75 days. Most radon detectors were horizontally installed; however, in some locations, detectors were vertically installed in consideration of the efficiency of monitoring.

In this study, the levels of occupational radon exposure were measured using three monitoring detectors at a height of the breathing zone of operators in the working spaces (approximately 1.5 m from the floor) in consideration of the exposure route of the respiratory system, and the radon monitoring detectors were installed and measured a total of 3 points per work (task) (≥2 points) located more than 0.3 m from the wall or ceiling and over 0.5 m from the floor. We also avoided installing radon detectors close to electronic equipment where electromagnetic waves may be generated and at specific locations without windows; ventilation systems, such as fans and air conditioning; or airflow paths (Fig. 1).

We also collected detailed qualitative information on occupational radon exposure, type of manufacturing industry, type of final product, raw material and process byproducts used, location of workplace (storage warehouse for raw materials, or the remainder of workplaces), type of process (*e.g.*, mixing, spraying, *etc.*), number of workers, task frequency and duration, and local exhaust ventilations installed and used.

Unlike manufacturing workplaces, radon exposure levels in underground public-use facilities (*e.g.*, communal areas, tunnels, warehouses, offices, *etc.*) were measured in at least 3 to 5 points according to the characteristics of the monitoring locations (sites), but the same monitoring detectors were used for the short-term (E-PERM®), long-term (Radtrak2® alpha track), and real-time (RAD7) measurements. Due to the unavailability of some detectors, short- and long-term radon measurements were conducted for one facility (B9), and short-term measurements were only collected for one facility (B11).

The short-term measurements performed using E-PERM® detectors in the underground public-use facilities were collected for more than 7 days in the same manner as described for the manufacturing workplaces, but the long-term measurements using Radtrak2® alpha track detectors were conducted for 7 to 73 days, which was shorter than those performed in the

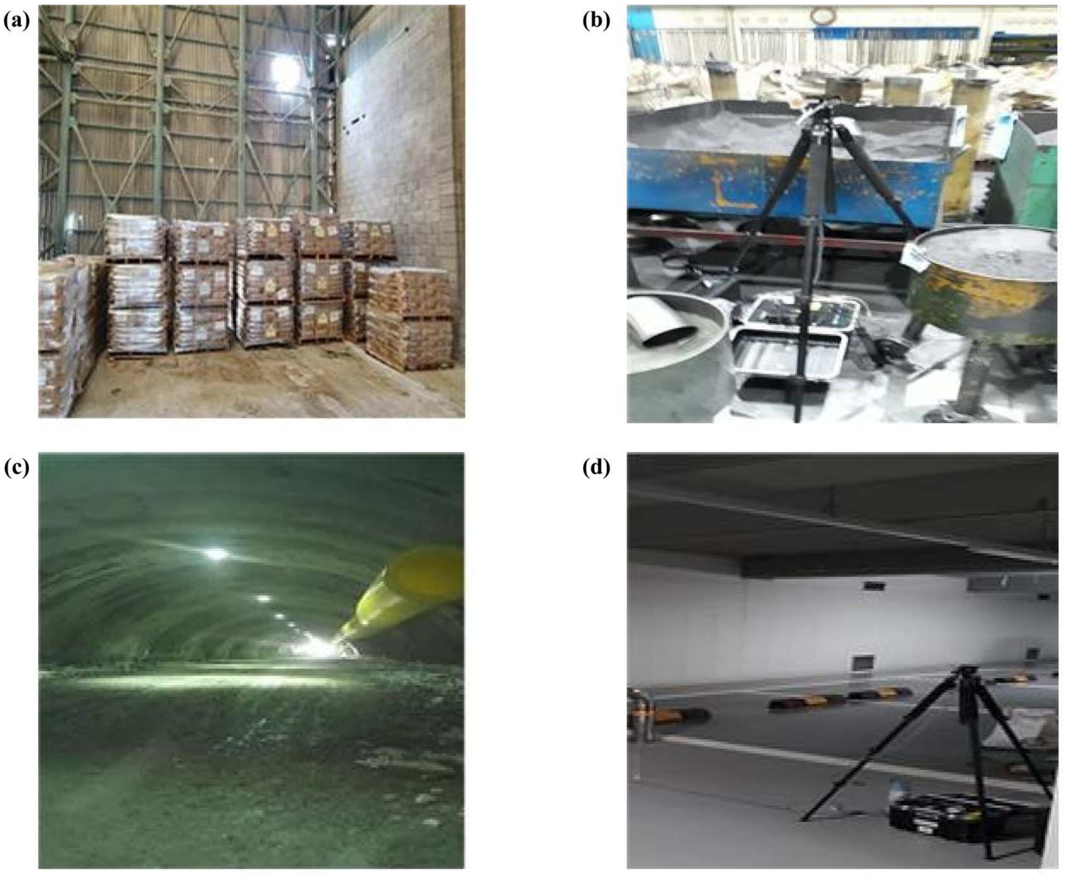

Fig. 1 Photographs of on-site radon monitoring (a) at a warehouse storing radon-containing raw materials; (b) during the moulding process at workplaces; (c) at an underground tunnel; (d) at underground parking lots in underground public-use facilities.

workplaces. The long-term radon measurements were required for a period similar to that of the workplaces, but some measurements were not completed due to repair at two facilities (B9 and B10). All measured radon concentrations were calculated using the international standard unit of becquerel per cubic metre (Bq m^{-3}).

2.3 Statistical analysis

In this study, we measured the short-term, long-term, and real-time radon exposure concentrations using three different monitoring devices at 10 manufacturing workplaces and 11 underground public-use facilities. Descriptive statistics, including the number of samples collected for each process and location, each value for radon measured at the workplaces and facilities, arithmetic mean (AM), standard deviation (SD), geometric mean (GM), geometric standard deviation (GSD), median, and range (min–max), were calculated. However, if only one real-time radon measurement was available, statistical analysis, including the means and standard deviations, was not performed.

We also assessed normality after converting all measured radon concentrations to the natural logarithms. Then, statistical analysis was performed using the parametric method. If the number of measured samples was less than 30, the nonparametric method was used to compare the mean radon levels for the real-time (RAD7) measurements. For the remainder of the radon measurements, the mean radon levels for many characteristics, such as the type of workplace, location, monitoring device, and task frequency, between the workplaces and underground public facilities were compared using an independent student's *t*-test (unpaired) and one-way analysis of variance (ANOVA). All tests were two sided. Here, p values <0.05 were considered statistically significant. All statistical analyses were performed using statistical software packages STATA version 16.1 (StataCorp LP, College Station, TX, USA) and R Statistical Software version 4.2.2 (R Core Team 2022).

3. Results

3.1 Characteristics of manufacturing workplaces and processes

The qualitative information on the general working environment and exposure characteristics of the 10 manufacturing workplaces selected as the study subjects is summarized in Table 1. These 10 workplaces are classified into various industries, such as A1 (casting of steel), A2 (casting of pig iron), A3 (manufacture of enamels, glazes, engobes and similar preparations for ceramic), A4, A5, A9 (manufacture of concrete tiles,

Table 1 Characteristics of the manufacturing workplaces and underground public-use facilities in this study

Classification	Location	Description of the monitoring site (type of industry)	KSIC[a] code	Number of workers	Duration of task	Frequency of task	Raw material	Total amount used (ton per year)	Use of local exhaust ventilation	Duration of monitoring (in days)	
										Short-term (E-PERM®)	Long-term (alpha track, RAD7)
Manufacturing workplaces	A1	Casting of steel	24 312	22	12 h per day	Intermittent or casual (irregularly performed)	Zircon	984	Yes	7	75
	A2	Casting of pig iron	24 311	4	16 h per day	Intermittent or casual (irregularly performed)	Silica fume	50	Yes	7	69
	A3	Manufacture of enames, glazes, engobes and similar preparations for ceramic	20 412	10	8 h per day	Intermittent or casual (irregularly performed)	Zircon	160	Yes	7	61
	A4	Manufacture of concrete tiles, roofing tiles, bricks and blocks (site 1)	23 324	50	8 h per day	Intermittent or casual (irregularly performed)	Zircon	220	Yes	7	63
	A5	Manufacture of concrete tiles, roofing tiles, bricks and blocks (site 2)	23 324	36	52 h per week	Intermittent or casual (irregularly performed)	Zircon	120	Yes	12	55
	A6	Manufacture of electrical carbon products and insulators (ceramic)	28 902	17	3–4weeks per year	Intermittent or casual (irregularly performed)	Zircon	102	Yes	7	77
	A7	Manufacture of unshaped refractory ceramic products (site 1)	23 212	30	8 h per day	Intermittent or casual (irregularly performed)	Zircon	600	Yes	7	63
	A8	Manufacture of basic iron	24 111	9	24 h per day (2 shifts, 3 teams)	24/7 operations (continuous)	Zircon sand	14	Yes	7	29
	A9	Manufacture of concrete tiles, roofing tiles, bricks and blocks (site 3)	23 324	58	8 h per day	Intermittent or casual (irregularly performed)	Zircon	260	Yes	22	56
	A10	Manufacture of unshaped refractory ceramic products (site 2)	23 212	10	8 h per day	Intermittent or casual (irregularly performed)	Zircon	34	Yes	11	67
Underground public-use facilities[b]	B1	Underground cavity at an international airport	—	—	—	—	—	—	—	7	73
	B2	Underground storage facility for gas	—	—	—	—	—	—	—	9	48
	B3	Underground tunnel (site 1)	—	—	—	—	—	—	—	7	41
	B4	Underground tunnel (site 2)	—	—	—	—	—	—	—	7	42

Table 1 (*Contd.*)

Classification	Location	Description of the monitoring site (type of industry)	KSIC[a] code	Number of workers	Duration of task	Frequency of task	Raw material	Total amount used (ton per year)	Use of local exhaust ventilation	Duration of monitoring (in days) Short-term (E-PERM®)	Long-term (alpha track, RAD7)
	B5	Underground office room	—	—	—	—	—	—	—	7	15
	B6	Underground warehouse (site 1)	—	—	—	—	—	—	—	8	19
	B7	Underground parking lot	—	—	—	—	—	—	—	7	15
	B8	Underground warehouse (site 2)	—	—	—	—	—	—	—	7	14
	B9	Underground machinery room	—	—	—	—	—	—	—	7	7
	B10	Underground warehouse (site 3)	—	—	—	—	—	—	—	8	8
	B11	Underground storage facility for chemicals	—	—	—	—	—	—	—	7	—

[a] KSIC: Korean Standard Industrial Classification. [b] No information on the number of workers, duration and frequency of tasks, raw materials and total amount used at the underground public-use facilities was collected.

roofing tiles, bricks, and blocks), A6 (manufacture of electrical carbon products and insulators), A7, A10 (manufacture of unshaped refractory ceramic products), and A8 (manufacture of basic iron).

Most of the manufacturing processes at the workplaces were automated, and the number of workers was relatively small, ranging from 4 to 58 individuals. In addition, the frequency of job tasks for most workers was intermittent or casual, but 3 groups of workers employed at the only company (A8) that manufactures basic iron performed 2 shifts for 24/7 consecutive hours per day. The total amount of raw materials used was the largest for A1 at 984 tons per year, and the smallest amount was noted for A8 at 14 tons per year. An electrostatic precipitator and ventilation facilities (local exhaust systems) were installed and operated in all workplaces. The main raw materials used at all workplaces were zircon or zircon sand except for A8, which used silica fume.

On the other hand, 11 underground public-use facilities included B1 (underground cavity space at an international airport), B2 (underground storage facility for gas), B3, B4 (underground tunnel), B5 (underground office room), B6, B8, B10 (underground warehouse), B7 (underground parking lot), B9 (underground machinery room), and B11 (underground storage facility for chemicals). No information on the working conditions and related characteristics of occupational radon exposure, including frequency and duration of the tasks, engineering controls, and operating procedures, was available, but we observed that most workers at the underground facilities mainly performed regular inspections, maintenance, and repair for the facilities and infrastructure.

3.2 Results of occupational exposure monitoring for radon

The overall mean levels of a total of 299 radon concentrations measured at 10 workplaces and 11 underground public-use facilities were 86.4 Bq m^{-3} (GM) and 133.0 ± 141.6 Bq m^{-3} (AM ± SD), respectively (Table 2). The mean radon concentrations measured at the underground facilities (GM 118.9 Bq m^{-3}) was significantly higher than that of the manufacturing workplaces (GM 68.3 Bq m^{-3}) ($p < 0.001$) (Fig. 2). The GMs were also calculated to be 60.7 Bq m^{-3} ($n = 91$) for the short-term measurements (using E-PERM®), 132.4 Bq m^{-3} for the long-term measurements (using the Radtrak2® alpha track) ($n = 176$), and 30.0 Bq m^{-3} for real-time measurements (using a RAD7 radon detector) ($n = 32$) [Table 2].

3.2.1 Manufacturing workplaces. The descriptive statistics on the mean levels of occupational radon exposure measured at 10 workplaces are summarized in Table 2. The GMs were calculated to be 50.5 Bq m^{-3} (A1, $n = 24$), 56.5 Bq m^{-3} (A2, $n = 18$), 52.7 Bq m^{-3} (A3, $n = 13$), 84.6 Bq m^{-3} (A4, $n = 17$), 87.9 Bq m^{-3} (A5, $n = 16$), 98.7 Bq m^{-3} (A6, $n = 16$), 91.3 Bq m^{-3} (A7, $n = 15$), 66.9 Bq m^{-3} (A8, $n = 15$), 56.4 Bq m^{-3} (A9, $n = 18$), and 63.2 Bq m^{-3} (A10, $n = 16$). Please refer to Table 2 for all calculated AMs. The GM of A6 was the highest at 98.7 Bq m^{-3}, and some measurements of three workplaces, including A4, A6 and A7, exceeded the OEL value of 600 Bq m^{-3}. Most short-term measurements at the workplaces were significantly lower than

Table 2 Summary statistics of occupational exposure monitoring for radon in the manufacturing workplaces and underground public-use facilities in Korea (unit: Bq m^{-3})[a]

		All combined			Short-term (E-PERM®)			Long-term (alpha track)			Real-time (RAD7)		
Classification	Location	N	GM(GSD)	AM ± SD	N	GM(GSD)	AM ± SD	N	GM(GSD)	AM ± SD	N	GM(GSD)	AM ± SD
Overall		299	86.4(2.7)	133.0 ± 141.6	91	60.7(3.1)	116.8 ± 182.1	176	132.4(1.8)	161.0 ± 118.4	32	30.0(1.5)	25.1 ± 14.3
Manufacturing workplaces	A1	24	50.5(2.1)	64.3 ± 46.1	7	41.3(2.8)	63.8 ± 70.1	14	67.8(1.6)	74.0 ± 30.8	3	20.4(1.2)	20.7 ± 4.4
	A2	18	56.5(2.0)	69.3 ± 45.4	5	64.9(2.3)	85.8 ± 73.2	10	73.2(1.3)	76.0 ± 21.8	3	18.9(1.3)	19.3 ± 4.6
	A3	13	52.7(2.6)	71.8 ± 45.0	4	19.4(2.7)	29.3 ± 32.9	8	92.4(1.5)	98.0 ± 31.2	1	32.7	32.7
	A4	17	84.6(2.4)	126.9 ± 156.9	5	83.4(3.4)	180.6 ± 292.5	10	114.1(1.5)	121.4 ± 39.5	2	19.6(1.3)	19.9 ± 4.3
	A5	16	87.9(2.0)	105.3 ± 53.6	5	88.1(2.0)	104.2 ± 62.7	10	103.9(1.7)	114.8 ± 45.4	1	16.4	16.4
	A6	16	98.7(2.3)	144.01 ± 179.8	5	200.4(2.4)	283.9 ± 288.5	10	82.9(1.4)	86.8 ± 23.9	1	16.4	16.4
	A7	19	91.3(4.1)	206.6 ± 297.6	6	85.3(12.2)	425.4 ± 480.7	12	108.9(1.3)	113.1 ± 30.5	1	16.4	16.4
	A8	15	66.9(5.1)	149.3 ± 141.4	4	15.3(5.5)	34.6 ± 44.2	8	224.8(1.9)	255.5 ± 107.2	3	18.9(1.3)	19.3 ± 4.7
	A9	18	56.4(2.5)	78.7 ± 59.0	5	27.6(2.2)	35.9 ± 30.6	10	108.8(1.5)	117.4 ± 48.8	3	20.8(1.2)	21.1 ± 4.2
	A10	16	63.2(2.6)	87.9 ± 59.2	5	22.4(1.8)	25.4 ± 13.1	10	121.2(1.4)	126.3 ± 37.3	1	16.8	16.8
Underground public-use facilities	B1	11	144.7(1.5)	155.8 ± 56.3	3	161.2(1.0)	161.3 ± 5.2	6	176.0(1.3)	182.1 ± 49.3	2	68.4(1.1)	68.4 ± 4.2
	B2	19	103.7(2.0)	120.5 ± 50.3	6	83.1(2.2)	105.4 ± 70.5	12	135.0(1.2)	136.7 ± 22.2	1	16.4	16.4
	B3	16	108.5(2.1)	129.0 ± 59.4	5	82.9(2.2)	104.8 ± 78.5	10	150.1(1.2)	152.4 ± 28.4	1	16.4	16.4
	B4	17	110.9(2.2)	142.5 ± 90.4	5	101.1(2.5)	142.5 ± 125.3	10	156.7(1.4)	166.0 ± 62.1	2	24.9(1.0)	24.9 ± 0.4
	B5	10	201.9(3.5)	324.9 ± 233.9	3	76.8(1.0)	76.8 ± 3.1	6	495.8(1.2)	500.3 ± 75.2	1	16.8	16.8
	B6	10	117.1(1.6)	126.5 ± 44.4	3	103.8(1.2)	104.8 ± 18.2	6	150.2(1.2)	152.2 ± 27.7	1	37.8	37.8
	B7	10	142.8(3.3)	246.4 ± 234.5	3	49.4(1.1)	49.4 ± 3.3	6	324.4(1.9)	381.7 ± 209.6	1	25.2	25.2
	B8	11	103.2(2.2)	129.2 ± 78.7	3	79.4(1.0)	79.4 ± 3.1	6	175.3(1.5)	184.7 ± 60.4	2	31.2(2.4)	37.3 ± 29.1
	B9	9	194.9(2.6)	274.6 ± 205.3	3	59.4(1.3)	61.2 ± 18.9	6	353.0(1.6)	381.3 ± 162.2	—	—	—
	B10	11	91.3(2.5)	131.5 ± 116.9	3	72.1(1.3)	73.6 ± 18.7	6	161.6(2.0)	196.0 ± 124.9	2	23.5(1.6)	24.8 ± 11.4
	B11	3	32.0(1.7)	34.9 ± 16.3	3	32.0(1.7)	34.9 ± 16.3	—	—	—	—	—	—

[a] GM: geometric mean; GSD: geometric standard deviation; AM: arithmetic mean; SD: standard deviation.

the long-term measurements, but the only mean levels of short-term measurements at A6 [200.4 Bq m^{-3} (GM) and 283.9 ± 288.5 Bq m^{-3} (AM ± SD)] were significantly higher than those of the long-term measurements [82.9 Bq m^{-3} (GM) and 86.8 ± 23.9 Bq m^{-3} (AM ± SD)] ($p < 0.05$).

The highest level measured for short-term monitoring with the E-PERM® detector for the moulding process of A7 was

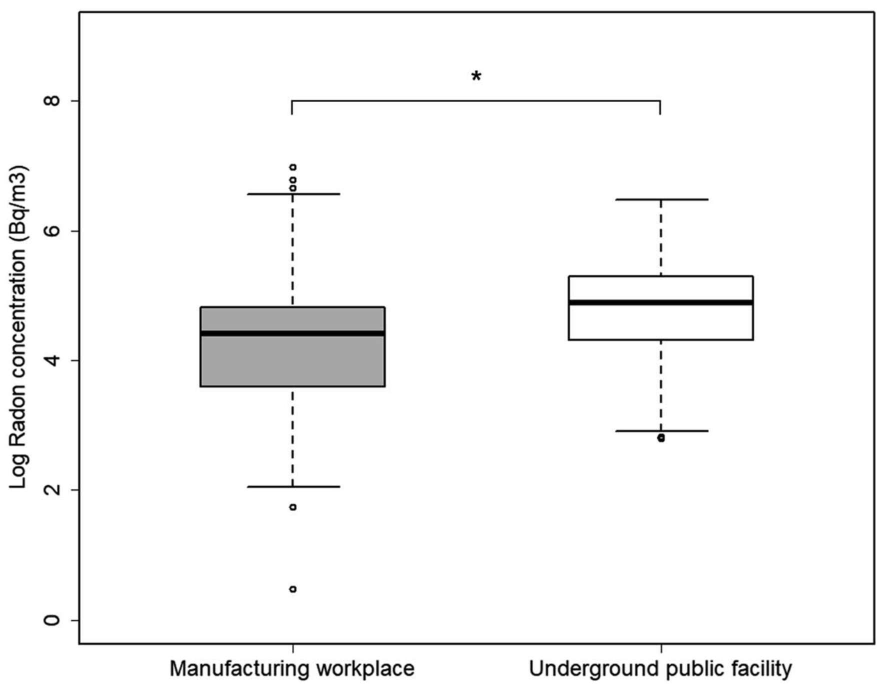

Fig. 2 Box plot of log-transformed radon concentrations measured at the manufacturing workplaces and underground public-use facilities, and the mean radon levels are significantly different ($p < 0.001$).

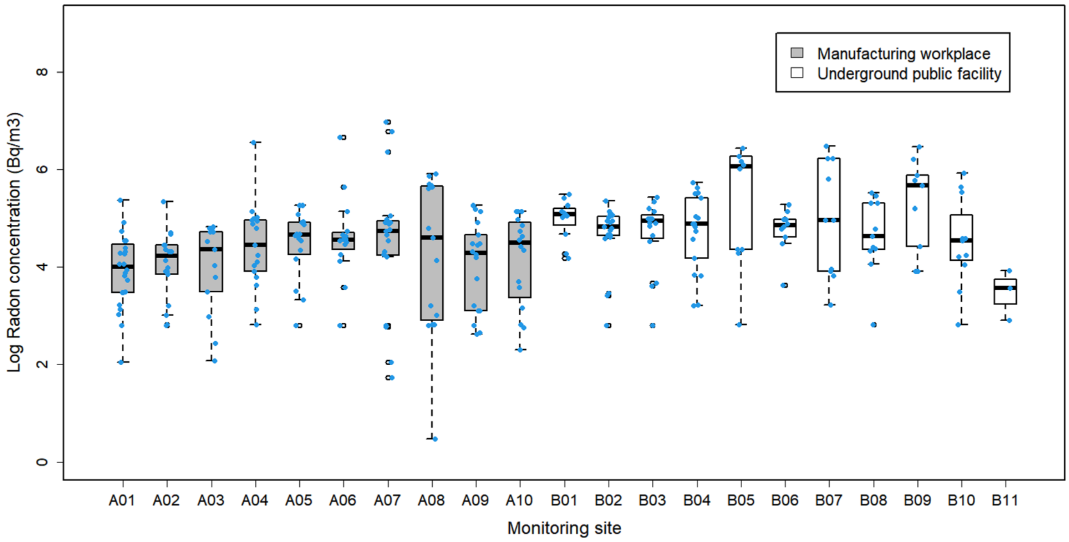

Fig. 3 Box plot of log-transformed radon concentrations measured at each monitoring site of workplaces and underground public facilities.

1066.3 Bq m^{-3}, and the second highest value was 874.5 Bq m^{-3} measured in the storage warehouse for raw materials. The workers at A8 were performing job tasks directly handling zircon sand and its process byproducts in two shifts with three groups for 24 hours, but the GM for short-time measurements using E-PERM® detectors was the lowest at 15.3 Bq m^{-3}. Box plots with dots of the radon measurements for each workplace are shown in Fig. 3.

3.2.2 Underground public-use facilities. Table 2 summarizes the statistics on the average radon concentrations measured using three different detectors at 11 underground public-use facilities. The GMs of radon concentrations for each facility were calculated to be 144.7 Bq m^{-3} (B1, $n = 11$), 103.7 Bq m^{-3} (B2, $n = 19$), 108.5 Bq m^{-3} (B3, $n = 16$), 110.9 Bq m^{-3} (B4, $n = 17$), 201.9 Bq m^{-3} (B5, $n = 10$), 117.1 Bq m^{-3} (B6, $n = 10$), 142.8 Bq m^{-3} (B7, $n = 10$), 103.2 Bq m^{-3} (B8, $n = 11$), 194.9 Bq m^{-3} (B9, $n = 9$), 91.3 Bq m^{-3} (B10, $n = 11$), and 32.0 Bq m^{-3} (B11, $n = 3$). Please see Table 2 for all calculated AMs.

In particular, the mean radon concentrations measured at B5 (underground research office room), B7 (underground parking lot), and B9 (underground machinery room) were significantly higher than those of the remainder of the facilities ($p < 0.05$). Most radon measurements exceeded the national reference level of 148 Bq m^{-3}, and some measurements even exceeded the OEL of 600 Bq m^{-3}. Furthermore, most short-term radon measurements were significantly lower than the long-term measurements ($p < 0.05$), which was similar to the trend noted at the manufacturing workplaces. However, no significant differences between short- and long-term radon concentrations were observed at the underground public-use facilities. Box plots with dots of the radon measurements for each facility are also shown in Fig. 3.

3.3 Comparison between the workplaces and facilities

Overall, the mean radon concentrations were 68.3 Bq m^{-3} (GM) and 109.7 ± 140.3 Bq m^{-3} (AM ± SD) at manufacturing workplaces ($n = 172$), and 118.9 Bq m^{-3} (GM) and 164.6 ± 137.8 Bq m^{-3} (AM ± SD) at underground public-use facilities ($n = 127$). The values at the underground facilities were significantly higher than those observed at the workplaces ($p < 0.001$) (Table 3). Similarly, the GM of short-term measurements for underground public-use facilities was 77.9 Bq m^{-3}, which was significantly higher than that of manufacturing workplaces at 50.0 Bq m^{-3} ($p = 0.046$). The GM of long-term measurements

Table 3 Comparison of mean exposure levels for radon between the manufacturing workplaces and underground public-use facilities by monitoring the duration (unit: Bq m^{-3})

Classification		*N*	GM(GSD)	AM ± SD	Median	Range	*p*-value
Overall	All combined	299	86.4(2.7)	133.0 ± 141.6	99.0	1.6–1066.3	—
	Manufacturing workplaces	172	68.3(2.7)	109.7 ± 140.3	82.6	1.6–1066.3	<0.001
	Underground public-use facilities	127	118.9(2.4)	164.6 ± 137.8	133.0	16.4–650.0	
Short-term (E-PERM®)	Manufacturing workplaces	51	50.0(4.0)	134.0 ± 236.0	45.6	1.6–1066.3	0.046
	Underground public-use facilities	40	77.9(1.9)	94.8 ± 64.9	78.6	18.2–308.7	
Long-term (alpha track)	Manufacturing workplaces	102	100.9(1.6)	114.2 ± 62.5	103.5	28.0–366.0	<0.001
	Underground public-use facilities	74	192.5(1.7)	225.6 ± 144.6	162.0	68.0–650.0	
Real-time (RAD7)	Manufacturing workplaces	19	19.5(1.2)	20.0 ± 4.7	16.8	16.4–32.7	0.014
	Underground public-use facilities	13	28.1(1.7)	32.6 ± 19.8	25.2	16.4–71.4	

Table 4 Comparison of mean exposure levels for radon between the manufacturing workplaces and underground public-use facilities by frequency of task (unit: Bq m^{-3})

Classification	Frequency of task	N	GM(GSD)	AM ± SD	Median	Range	p-value
Manufacturing workplaces	24/7 operations (continuous)	16	78.0(5.1)	188.8 ± 208.8	110.4	1.6–780.9	<0.001
	Intermittent or casual (irregularly performed)	156	67.4(2.5)	101.5 ± 129.5	80.0	5.7–1066.3	
Underground public-use facilities	—	127	118.9(2.4)	164.6 ± 137.8	133.0	16.4–650.0	

for the facilities was 192.5 Bq m^{-3}, which was significantly higher than that of the workplaces at 100.9 Bq m^{-3} ($p < 0.001$) (Table 3).

Furthermore, the average radon levels measured in the storage warehouse for raw materials of each workplace were 77.6 Bq m^{-3} (GM) and 128.6 ± 170.2 Bq m^{-3} (AM±SD) ($n = 38$), which was significantly higher than those noted for the remainder of the workplaces (including the process) at 65.9 Bq m^{-3} (GM) and 104.3 ± 129.5 Bq m^{-3} (AM ± SD) ($n = 134$) ($p < 0.05$). Considering the task schedules and frequency, only the workers at A8 performed 24 h rotating shift work among all workplaces, whereas the remainder of the workers performed their tasks intermittently. In this regard, we observed significant differences when comparing all radon measurements by frequency of task ($p < 0.001$), which is one of the most important factors affecting the levels of occupational radon exposure. In addition, the underground public facilities had the highest mean radon level compared to the workplaces (Table 4).

4. Discussion

To the best of our knowledge, this is the first study monitoring and quantitatively evaluating short-term, long-term, and real-time radon measurements at Korean nationwide manufacturing workplaces and underground public facilities where workers might be exposed to radon from raw materials, byproducts of various processes, or NORMs. More importantly, we found that the mean radon level in the underground facilities was approximately 1.8-fold higher than that in the workplaces. We anticipate that the low radon levels at the workplaces were because most job tasks were intermittently performed under circumstances with the installation and operation of effective engineering controls and ventilation systems. On the other hand, high radon levels at the underground public-use facilities occurred because engineering controls, regular monitoring and exposure assessment, and administrative management for occupational radon exposure were insufficient; thus, the workers could be exposed to much higher levels of radon in the form of NORMs during inspections, maintenance, and repairs at the facilities.

Prior to the present study, quantitative data and detailed information on the characteristics of occupational radon exposure at workplaces and underground facilities were lacking and limited. In Korea, the Occupational Safety and Health Research Institute (OSHRI), an affiliated institute of Korea Occupational Safety and Health Agency (KOSHA), conducted a study showing that the mean radon level was 24.0 ± 13.8 Bq m^{-3} at seven cement manufacturers.[51] In another study, the mean radon levels were 58.9 ± 50.9 Bq m^{-3} at subway tunnels and 140.4 ± 66.6 Bq m^{-3} at the underground drainage pumps of metropolitan subway stations.[52] Chung *et al.* also reported that the mean radon levels were 14.3 Bq m^{-3} in fertilizer manufacturing, 11.7 Bq m^{-3} in gypsum-board manufacturing, and 21.9 Bq m^{-3} in the cement manufacturing processes.[30] However, the number of radon measurements was relatively small and restricted to only certain processes or workplaces and subway stations.

In Australia, the mean radon level measured at public workplaces was 10.5 ± 11.3 Bq m^{-3}.[53] In Spain, approximately 27% of indoor radon concentrations measured in five different sectors (*e.g.*, education, public administration, health care, tourist and private) of Spanish workplaces exceeded an international threshold level of 300 Bq m^{-3}, and the median was 129.5 Bq m^{-3}. In addition, the authors observed high levels of radon in the Galicia region, thus concluding that the geographical locations had important implications for the indoor radon concentrations.[45] In a Canadian population-level study, occupational radon exposures were evaluated. The average annual effective dose was 0.21 mSv, which was significantly lower than that of residential dwellings, 1.8 mSv, but the annual effective dose of radon for Canadian miners was 0.80 mSv.[54]

In the UK, the average levels of winter-corrected radon concentrations ($n = 3539$) measured in various workplace basements of radon-affected areas, including banks, education, health care, industry, office, retail, *etc.*, were 647 ± 3173 Bq m^{-3} (AM ± SD) and 147 Bq m^{-3} (GM), which were significantly higher than those of the nonaffected areas at 185 ± 634 Bq m^{-3} (AM ± SD) and 62 Bq m^{-3} (GM) ($p < 0.01$).[55] In 2019, the mean level (AM ± SD) of indoor radon concentrations measured in 12 Bulgarian rehabilitation hospitals was 102 ± 191 Bq m^{-3}, ranging from 19 to 2550 Bq m^{-3}. However, the effective doses for hospital workers did not exceed the exposure limit of 1 mSv per year.[48]

As discussed above, occupational radon exposure levels in various workplaces in Korea and several Western countries were lower than the values reported in this study. Some measurements exceeded the domestic or international exposure limits, but the levels of occupational radon exposures were well controlled and maintained below the exposure limits using engineering controls, such as ventilation and local exhaust systems, in the workplace and were effectively controlled under robust legal regulations and administrative management systems.

On the other hand, the indoor radon levels measured in residential housing and public-access buildings were shown to be the same as or somewhat lower than those observed in our study. In Korea, a study evaluating indoor radon levels in underground, semiunderground, and single-story dwellings revealed values of 130.2 ± 138.3 Bq m^{-3} (AM ± SD) and 101.7 Bq m^{-3} (GM).[56] The mean level of indoor radon measured for 15 residential housings and underground public-use facilities was 297.8 Bq m^{-3}.[57] Ji *et al.* also reported that the indoor radon levels in the winter season for private households in Chungcheong Province of Korea were 168.3 ± 193.3 Bq m^{-3} (AM ± SD) and 106.2 Bq m^{-3} (GM).[58]

In another nationwide study, a large-scale radon monitoring survey was conducted in 5600 households and showed an annual mean of 62.1 ± 66.4 Bq m^{-3}.[59] In 2015, the mean radon levels measured in several subway platforms and underground parking lots were 37.3 ± 17.1 Bq m^{-3}.[31] Another study reported that the mean radon concentrations in the offices at ground level and basement rooms of six commercial buildings in Seoul were 27.9 Bq m^{-3} and 42.9 Bq m^{-3}, respectively. These results indicate that the radon concentrations in the basement were significantly higher than those at the ground level.[60] In a recent study, the mean radon level at subway platforms and station offices was 67.9 ± 97.7 Bq m^{-3}, and the mean level of the underground pump stations was 86.5 ± 142.2 Bq m^{-3}. These results are similar to the results of the present study.[32]

In several foreign studies, the indoor radon concentrations measured in urban public buildings located in the northwestern region of Portugal in 2018 exceeded a national legal limit of 300 Bq m^{-3} and the WHO limit of 100 Bq m^{-3}, and the average radon concentrations in the winter and summer seasons were 643 ± 188 Bq m^{-3} and 643 ± 176 Bq m^{-3}, respectively. For radon risk assessment, the indoor effective doses, which were calculated to be 3.6 mSv per year for both winter and summer, also exceeded the limit of 1 mSv per year recommended by the ICRP.[61] In Finland, the means (AMs) of indoor radon levels in daycare centres and schools were 86 Bq m^{-3} and 82 Bq m^{-3}, respectively. The proportions of indoor radon concentrations exceeding a national reference level of 300 Bq m^{-3} were 8% for daycare centres and 14% for schools. The authors concluded that radon levels in workplaces and public-access buildings were lower than those in homes (mean 96 Bq m^{-3}).[62] In a systematic review, the mean indoor radon levels for dwellings, schools, and office buildings in China were 54.6 Bq m^{-3}, 56.1 Bq m^{-3}, and 54.9 Bq m^{-3}, respectively. The authors found that several factors, such as seasons, climate regions, ventilation, new decoration buildings, and soil, were associated with high indoor radon levels.[63]

In the present study, high peak exposure was observed during some manufacturing processes (*e.g.*, moulding, mixing, coating, *etc.*) that involve directly handling of radon raw materials or at storage warehouses of the workplaces when monitoring the short-term measurements using E-PERM® detectors, whereas high radon levels were generally observed in the underground public facilities when monitoring the long-term measurements using Radtrak2® alpha track detectors. In particular, high radon levels exceeding an exposure limit of 600 Bq m^{-3} were observed in a warehouse of A4 (703.5 Bq m^{-3}), the fibre collection process of A6 (780.9 Bq m^{-3}), and a warehouse (874.5 Bq m^{-3}) and moulding process (1066.3 Bq m^{-3}) of the A7 workplace.

On the other hand, relatively low variation in the radon exposure levels for each monitoring point was observed at the underground public-use facilities compared to the workplaces. The coefficient of variation (CV) was 83.7% for underground public facilities and 127.9% for workplaces. In underground public-use facilities, the only three radon measurements exceeding an exposure limit of 600 Bq m^{-3} were 623.0 Bq m^{-3} in an underground office room (B5), 650.0 Bq m^{-3} at an underground warehouse (B8), and 638.0 Bq m^{-3} in an underground office room (B9). Therefore, the radon levels monitored in the underground public facilities were significantly higher than those at the workplaces, but no high peak exposure exceeding 1000 Bq m^{-3} was observed.

In several previous studies, the authors reported that high indoor radon levels are likely to be associated with several environmental factors, such as season, cold climate region, basement, new building materials, ventilation, geological location, and soil properties. Therefore, the high levels of indoor radon exposure measurements in the underground public-use facilities observed in this study might be caused by some of these factors mentioned above.

Furthermore, the annual effective doses and lifetime risk of lung cancer were estimated using radon measurement results.[10,61,64,65] The average radon concentrations obtained from these previous studies were similar and comparable to the mean radon levels from our study; thus, it is expected that the annual effective dose estimated using our radon measurements might exceed 1 mSv per year or that the lifetime risk of lung cancer could be significantly increased. However, the estimated results from health risk assessment are out of scope for the present study. Therefore, it is suggested that comprehensive risk assessment and epidemiological studies using radon monitoring data collected from the present study should be conducted to quantitatively estimate and evaluate the potential health risks for workers in the future.

Regarding the representativeness of our study subjects, we collected detailed information on a total of 66 manufacturing companies directly handling monazite powder from a large-scale nationwide survey report published by MoEL. Therefore, the study subjects for whom radon can be monitored on site were randomly selected, and a senior-level worker, who had worked for the longest period of time and knew every detail and procedure of the performed job task, participated as a representative of similar exposure groups (SEGs) in monitoring occupational radon exposure at each workplace and facility. Three monitoring points were selected for each unit process or job task at the workplaces, whereas three to five points were selected for the underground facilities considering their large size. We considered the worst-case scenario because radon was monitored and evaluated for those monitoring points expected to have the highest exposure potential at each point of the workplace and underground public facility.

Differences in the monitoring periods and locations were observed at the workplaces and underground facilities; however, we anticipated that the findings are representative and reliable because the radon exposure levels were monitored at a worker or point location representing the process- or task-based SEGs. In fact, the same process or job task was not performed at every workplace and facility; thus, the levels and characteristics of occupational radon exposure were not the same. In addition, the period of long-term radon monitoring was not sufficient at some underground facilities; thus, there might be a limitation on the lack of consistency. In future studies, it is necessary to monitor occupational radon exposure in workers, places or points where the monitoring results are more consistent, reliable, and reproducible for a sufficient long-term period.

There are limitations in this study. First, we were not able to clearly identify where the high levels of occupational radon exposure in the underground facilities came from or the main reason for the radon exposure among several factors, such as season, geographical location, low ventilation rate, use of local exhaust ventilation, type of building materials, and construction year. Second, this study was conducted to measure radon exposure levels in nationwide workplaces and underground public-use facilities identified from the MoEL's survey report, so the sample size was larger than that of other previous domestic studies. However, a few workplaces and facilities were excluded due to unexpected reasons and situations.

The number of days for long-term radon measurements at B9 and B10 facilities was relatively shorter than those at the other facilities (<8 days), and the long-term measurement at the B11 facility was not collected due to unexpected inspection and maintenance at the facilities and of the related infrastructure. In this regard, we performed sensitivity analysis to determine how the radon measurement collected for shorter durations affects the results of statistical analysis. The radon measurements at the underground public-use facilities represented approximately 7.7% of the total number of samples, which is within 10%, and no significant difference in the overall mean levels (AMs and GMs) of radon measurements was observed before and after removing the missing values ($p > 0.05$) (data not shown). Therefore, we included all radon measurements (<8 days) for the data analysis in this study.

Furthermore, we did not measure indoor and outdoor temperature and relative humidity. Several previous studies have shown that indoor radon concentrations are negatively correlated with outdoor temperature[66] and outdoor relative humidity[67] but positively correlated with indoor temperature[68] and indoor relative humidity.[69] In another experimental study, it was reported that the relationships between indoor radon concentration and outdoor temperature and relative humidity could be changed to either a positive or negative correlation based on the presence or absence of air exchange between internal and external environments. More importantly, the authors emphasized that the outdoor temperature has a greater effect on the indoor radon concentrations.[70]

Finally, indoor radon concentrations were measured in most workplaces and underground facilities over the long-term (≥30 days), so the effects of outdoor environmental parameters, such as temperature and relative humidity, were already considered and applied. In addition, the mean radon levels of the open facilities, such as underground tunnels and parking lots, were not significantly lower than those of the closed facilities, such as gas storage rooms and warehouses. However, we still cannot exclude the possibility of variations in indoor radon concentrations affected by environmental parameters (outdoor temperature and relative humidity) at some open facilities, such as underground tunnels and parking lots, in the summer season. Therefore, it is highly suggested that various environmental parameters, including outdoor temperature, relative humidity, and wind speed, are simultaneously measured with indoor radon concentrations in future studies.

For these reasons, our study results cannot be applied to all workplaces and underground facilities in Korea or represent the overall radon exposure levels at different periods, sites, or situations.

Despite these limitations, the present study quantitatively measured, evaluated, and compared radon exposure levels at manufacturing workplaces in various industries and situations as well as underground public facilities in Korea. We were also able to successfully collect, build, and analyse the quantitative datasets and information on the characteristics and patterns of occupational radon exposure at each site. Furthermore, we found that workers might be exposed to higher radon levels from radon raw materials or NORMs, which has not been clearly identified by many previous studies. Based on our study findings, we suggest that occupational and environmental health professionals regularly monitor and evaluate radon exposure levels and health risks in accordance with relevant laws and regulations such as the Occupational Safety and Health Act at other workplaces and underground public facilities where there might be unintentional or unexpected radon exposures in the form of NORMs for workers.

5. Conclusions

In summary, we found that workers at underground public-use facilities could be unintentionally exposed to higher radon levels resulting from NORMs. We emphasize that administrative regulations, engineering controls, ventilation systems, respiratory protective equipment, and other related infrastructure should be strengthened and upgraded to reduce the high levels of potential radon exposure in the form of NORMs at underground facilities as well as at workplaces where radon-containing raw materials are used.

Robust administrative management and regulatory activities should be implemented with significant changes in work or job task patterns, operating procedures and cycles, identification of potential radon exposure sources and process byproducts, and prioritization of the most important factors for advanced management and improvement from the viewpoint of environmental health safety.

We also suggest that the Korean Occupational Safety and Health Act strengthens the regulations related to occupational exposure management for radiation and radon, thus establishing a more comprehensive control system to regularly monitor, evaluate, and reduce the levels of occupational radon exposure to the NORMs. In doing so, we can protect workers' health and safety from potential radon exposure at various workplaces and underground public-use facilities in the future.

Author contributions

Conceptualization, D. L., and S. S.; methodology, S. L., D. L., and S. S.; investigation, D. L., and S. S.; formal analysis, S. L., and D. L.; writing—original draft preparation, S. L., D. L., and S. S.; writing—review and editing, S. L., D. L., and S. S.; project administration, D. L., and S. S.; supervision, S. S. All authors have read and agreed to the published version of this manuscript.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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