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Rational establishment of radon exposure standards for dwellings and workplaces

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ABSTRACT

Background: Radon is a normally occurring radioactive material, which is designated as a class 1 human carcinogen. Therefore, it is important to control radon exposure in dwellings and workplaces. ***Methods:*** The radon guidelines of 32 countries across Europe, North America, and Asia were examined to determine rational radon exposure standards for minimizing radon risk in dwellings, offices, and workplaces. The exposure standards were classified as standards for people in dwellings and offices, where radon exposure can occur through construction materials, and standards for workers exposed to radon at industrial sites, where they directly handle products containing radioactive matter such as raw materials and by-products from processing. ***Results:*** The examination results showed that in South Korea, the advisory reference level (ARL) for dwellings is set to 148 Bq/m^3. Moreover, ARLs are set for subway stations, libraries, medical institutions, and indoor parking lots, but there are no radon exposure standards to protect workers in manufacturing sites, officers, and other workplaces. In other countries, the ARL or the mandatory reference level (MRL) are usually regulated between 148–400 Bq/m^3 for dwellings and public-use facilities, and between 200–1,000 Bq/m^3 for workplaces. ***Conclusion:*** It is recommended to use 148 Bq/m^3, which is the standard set by the U.S. Environmental Protection Agency, for dwellings and workplaces. For workplaces, it is recommended to set the exposure standard between 400 Bq/m^3, which is the level adopted in most European Union member countries, and 1,000 Bq/m3, which is the reference level recommended by the International Commission on Radiological Protection.

Keywords: *Dwellings, offices, workplaces, radon, exposure standards.*

INTRODUCTION

In South Korea, bracelets, necklaces, cushions, and other everyday products that generate anions are in demand because anions are advertised as improving body balance and stamina, promoting metabolism, and aiding in the stabilisation of nerves or recovering from fatigue. However, the scientific bases for these presumed effects are weak. To generate anions, monazite is used as an additive in small quantities. Monazite is a representative thorium mineral and contains natural radionuclides such as ^{232}Th and ^{238}U and their decay series. According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), ^{232}Th and its decay series radionuclides have a radioactivity range of 5-350 Bq/g, and the radioactivity of ^{238}U and radon progeny are known to be approximately 10% of that of ^{232}Th (1).

Among them, the radionuclide that is a cause for concern is radon (^{222}Rn). Radon is a normally occurring radioactive material (NORM) with a half-life of 3.8 d. It is a colourless and odourless noble gas that is contained in rocks, soils, and construction materials, and emits alpha particles, beta particles, and gamma-ray. Radon decay products are easily adsorbed into dust and when they are inhaled into the lung, they emit radiation while being decayed, which can cause lung cancer. Radon is designated as a class 1 human carcinogen [2, 3]. According to the U. S. Environmental Protection Agency (EPA), 62 out of 1,000 smokers (6.2%) exposed to 4 pCi/L(148 Bq/m^3) of radon, which is the mandatory reference level (MRL), during the entire lifetime could develop lung cancer. This is estimated to be five times higher risk than dying in a car accident. The incidence of lung cancer in smokers is approximately eight times higher than that in non-smokers [4].

The risk of radon exposure may vary by concentration, period of exposure, indoor ventilation, etc. In particular, the risk of human exposure through long-term inhalation can increase in indoor spaces in winter when ventilation is poor due to cold weather. It has been reported that in indoor spaces, approximately 90% of the total pathways for human exposure to radon is the inhalation of indoor air, whereas exposure through other means such as water intake is insignificant [5]. Radon can enter indoor spaces by various ways but the most common sources are soils and rocks except in some cases where radon is included in construction materials. Radon flows into the indoor environment through cracks on floor slabs of buildings by the diffusion and convection processes resulting from the differences in pressure and temperature between the indoor and outdoor spaces of buildings. Once radon enters the indoor space, it is adsorbed, deposited, and accumulated on the surrounding walls [6, 7].

Because radon is a radioactive matter, the effects of radiation need to be considered in the event of radon exposure. The largest risk of exposure to radon and radon decay products is from the ionising radiation exposure. Two factors are associated with the health risks posed by radon, namely, radon concentration and dose. The unit of radon concentration is Bq/m^3, and the radon dose is expressed in mSv, which is the committed effective dose. Radon concentration and radon dose are different physical quantities, and a conversion factor is used to evaluate the dose from radon exposure. The dose conversion factor of radon differs slightly depending on the advisory institution and researcher [8]. The radiation risk of radon can be reduced with reasonable cost. To achieve this goal, it is important for the government to limit radon exposure, institutionalise the standards for high-risk areas, establish guidelines, and educate workers regarding radon-related risks. Currently, South Korea does not have radon exposure standards to protect the health of workers, and has an inadequate radiation safety management system for raw materials such as monazite. The International Commission on Radiological Protection (ICRP), the World Health Organization (WHO), and the International Atomic Energy Agency (IAEA) are continuously encouraging countries to establish a radon management programme. They have recommended the enforcement of government policies such as radon mandatory reference level (MRL) settings for dwellings and workplaces, radon management guidelines for buildings, radon concentration survey before construction of new buildings, and limitation of the concentration of natural radioactive elements inside construction materials. However, even the IAEA has never released recommendations for the regulation of everyday products such as necklaces, bracelets, seat cushions, and beds.

This study examined the radon guidelines in Europe, North America, and Asia where radon-related research is active, to provide basic data not only for South Korea, which is preparing for the establishment of new radon exposure standards and improvement of current standards, but also for other countries that need to improve their radon management programmes. To this end, we first investigate the existing guidelines for radon exposure in countries and institutions that have well-established radon exposure management programmes and propose realistic and rational exposure standards based on the results.

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MATERIALS AND METHODS

Domestic and overseas institutions related to radon exposure were identified and the detailed items for which guidelines are set were examined. This study investigated 32 countries that have radon guidelines, which include 24 countries in the European Union (EU), 6 countries in Asia, and 2 countries in North America. To obtain information related to the reference level of radon in each country, we searched the websites of the related government and research institutions in the country and reviewed relevant studies. While examining the radon guidelines of each country, we considered two major aspects the reference level and exposure standard. We considered the reference level for workers who work daily in offices where radon may be generated through construction materials, as well as the exposure standard for workers who work in places such as subways, and tunnels, where they can be exposed to radon, or handle raw materials, by-products from processing, etc., that contain radioactive materials. The MRL is a reference level that is stipulated by a law or regulation, and is legally binding whereas the reference level that is not legally binding but voluntary intervention is required to reduce the radon concentration is called an advisory reference level (ARL).

RESULTS

Domestic

The basic laws on radon management in South Korea are the "Protective Action Guidelines against Radiation in the Natural Environment" of the Nuclear Safety and Security Commission (NSSC) and the "Indoor Air Quality Control in Public-Use Facilities, etc. Act" of the Ministry of Environment.

Article 2 of the "Protective Action Guidelines Against Radiation in the Natural Environment" defines the radiation in a living zone as the radiation emitted from natural radionuclides contained in source materials, by-products from processing and processed products, cosmic rays, terrestrial radiation, and radiation emitted from radioactive substances contained in scrap metals collected domestically or overseas and sold or recycled. According to this law, the country must provide policies required for safe management of radiation in a living zone to protect the health of people and the environment from radiation. Consequently, the NSSC establishes comprehensive plans for radiation protection around a living zone every five years and implements policies in accordance with the annual enforcement plan. The first comprehensive plan for radiation protection in a living zone (2013–2017) included factual surveys of major industries with raw materials and by-products from processing that contain natural radioactive materials, and it encouraged the status management of radon exposure through registration of workers in such industries. The second comprehensive plan for radiation protection in a living zone (draft) (2018–2022) focuses on the advancement and improvement of the effectiveness of the safety management system, including improvements for some shortcomings that had been observed during the implementation process of the safety management system for radiation in a living zone. Furthermore, to define detailed safety standards, the Act prescribes the establishment of regulations for the safety control of radioactive rays in a living environment. The regulations define the radiation concentration and quantity of radioactive raw materials and by -products from processing the standard for radiation exposure from processed products, and the standard for monitored radiation concentration. They present the detailed standards for radiation in a living zone in terms of external exposure due to processed products. If any processed product does not meet the above safety standards, the manufacturer must disclose this fact and take measures according to the plan, such as complementation, replacement, collection, disposal, etc., of the radioactive source. However, this regulation does not include a standard for internal exposure via inhalation and other key scenarios for exposure. Furthermore, according to the Indoor Air Quality

Control in Public-Use Facilities, etc. Act, the Ministry of Environment established the Indoor Radon Management Total Plan (2007–2012) and promoted the construction of radon measurement base, identification of radon exposure status, and management of high-concentration exposure paths to ensure an indoor environment safe from radon exposure. However, the current law does not have a concrete basis for safety management of indoor radon even though radon is included in the category of indoor terrestrial radiation. The Ministry of Environment regards radon as one of 17 indoor contaminants according to the indoor radon reduction guideline, and sets the ARL for air quality maintenance in public-use facilities as 148 Bq/m^3 in accordance with the U.S. residential standards. However, because the purpose of this law is to manage air quality in terms of indoor contaminant management rather than protection from radiation, the IAEA recommended the South Korean government in 2014 to establish and implement a national action plan that reflects the national reference level for radon and the circumstances specific to the regions of interest.

Radon was first regulated under indoor air quality management in 1996 through the Underground Living Space Air Quality Management Act, which was revised as the Indoor Air Quality Control in Public-Use Facilities, etc. Act (hereinafter referred to as "Public-Use Facilities Act"). Furthermore, the target areas for application were expanded from two facilities namely, subway stations and underground shopping malls, to 17 facilities including libraries, medical institutions, and passenger terminals [9]. The number of managed pollutants was also enhanced to 10 items, and the targeted buildings were obligated to abide by the maintenance standards and ARLs depending on the pollutant, which provided greater opportunity for systematically managing the indoor air quality. The Ministry of Education defined 12 items including particulate matter (PM) 10 or lower fine dusts, radon, and total volatile organic compounds (TVOC) as pollutants in schools. The Ministry of Employment and Labour and the Ministry of Health and Welfare also regulated the target matter for pollution management including PM10, which covered carbon dioxide and carbon monoxide, but radon was excluded [10, 11]. The Ministry of Land, Infrastructure and Transport requires parking lots of size 2,000 m^2 or smaller, which are not included in the Public-Use Facilities Act, to perform pollution management and maintain appropriate brightness [11]. Thus, with regard to the guidelines for radon, ARLs are set for Public-Use facilities monitored by the Ministry of Environment and schools monitored by the Ministry of Education, which are critical areas for radon management, but there are no radon exposure standards to protect office workers and other workers in manufacturing sites [10]. The related data are summarised in table 1.

Table 1a. Domestic indoor air quality standards .

(a) Air quality standards

Pollutants / Public-use facilities	Fine dusts (PM10) (㎍/㎥)	Carbon dioxide (ppm)	Form aldehyde (㎍/㎥)	Total floating bacteria (CFU/㎥)	Carbon Monoxide (ppm)
a. Subway stations, underground shopping malls, waiting rooms of railroad stations, waiting rooms of passenger car terminals, waiting rooms of port facilities, passenger terminals of airport facility, libraries, museums and art galleries, large-scale stores, funeral halls, movie theatres, schools, exhibition facilities, internet computer game sales facilities, and Commercial bathhouses	150 or lower	1,000 or lower	100 or lower	-	10 or lower
b. Medical Institutions, postpartum care centres, elderly care facilities, and nursery schools	100 or lower			800 or lower	
c. Indoor parking lots	200 or lower			-	25or lower
d. Indoor sports facilities, indoor performance arenas, business facilities, and Multi-purpose buildings		-	-	-	-

Table 1b. Advisory reference level (ARL).

(b) ARL

Pollutants / **Public-use facilities**	**Pollutants (ppm)**	***Radon (Bq/m³)***	**Total volatile organic compounds (μg/m³)**	**Fine dusts (PM2.5)(μg/m³)**	**Moulds (CFU/m³)**
a. Subway stations, underground shopping malls, waiting rooms of railroad stations, waiting rooms of passenger car terminals, waiting rooms of port facilities, passenger terminals of airport facility, libraries, museums and art galleries, large-scale stores, funeral halls, movie theatres, schools, exhibition facilities, internet computer game sales facilities, and business facilities of bathhouses	0.05 or lower	*148 or lower*	500 or lower	-	-
b. Medical Institutions, postpartum care centres, elderly care facilities, and nursery schools			400 or lower	70 or lower	500 or lower
d. Indoor parking lots	0.30 or lower		1,000 or lower	-	-

Table 2. Radon exposure standards for dwellings and workplaces.

	Dwellings		**Workplaces**	
	Advisory level	**Enforced level**	**Advisory level**	**Enforced level**
Australia	400	-	400	-
Austria	400		400	
Belgium	400			
Canada	-	400	-	-
China	400	-	-	-
Czech	200	1000	-	-
Denmark	-	400	-	400
Estonia	-	1500	-	-
Finland	-	400	-	400
France	400	-	-	-
Germany	400	-	-	-
Greece	400	-	400	-
Ireland	200	-	200	-
Israel	400	-	400	-
Italy	400	-	-	-
Japan	600	-	-	-
Latvia	1000	-	1000	-
Lithuania	-	400	-	400
Luxembourg	-	148	-	-
Netherland	400	-	-	-
Norway	400	-	400	-
Portugal	400	-	-	-
South Korea	200	-	-	-
Russia	-	800	-	800
Slovak	-	1000	-	1000
Slovenia	1000	-	1000	-
Spain	400	-	-	-
Sweden	200	400	-	400
Switzerland	400	-	400	-
Syria	400	-	400	-
UK	200	-	-	400
USA	148	-	-	3700

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International

Dwellings

The review of radon guidelines of 24 member countries of the EU (28 countries), which have standards for existing dwellings, show that the guideline range for dwellings is 148-400 Bq/m^3 for Western European countries including Austria, Belgium, Denmark, Finland, Germany, Greece, Ireland, Luxembourg, Sweden, and United Kingdom. On the other hand, the guideline range for existing dwellings in Eastern European countries including Czech Republic, Estonia, Latvia, Lithuania, Slovakia, Slovenia, and Russia is 200-1,500 Bq/m^3, which is relatively broad (figure 1). Approximately 67% of these EU countries have set 400 Bq/m^3 as the guideline for existing dwellings, whereas Luxembourg, Finland, Norway, Sweden and Russia have adopted the MRL. For new dwellings, many countries have applied a stricter ARL (200 Bq/m^3) than for existing dwellings [12, 13].

In USA and Canada, the standard ARL is set at 148 Bq/m^3 and 200 Bq/m^3, respectively, with no distinction between existing and new dwellings [4, 14]. Australia and Israel have set 200 Bq/m^3 as the standard for both existing and new dwellings. In China, the standards for existing and new dwellings are 400 Bq/m^3 and 200 Bq/m^3, respectively. Japan follows the reference level (600 Bq/m^3) recommended by the ICRP 60. In most EU member countries, the government or related institutions not only supervise the implementation of the orders and recommendation related to radon management, but also perform various regulatory activities such as verifying compliance with its provisions. In Finland, Sweden, and UK, the local government is responsible for supervision. In Russia, Latvia, Lithuania, Slovakia, and Switzerland, the regulatory authority is in charge of supervision for protection from radiation. In Norway, the local governments supervise radon-related regulations, and in the USA, radon management programmes are mostly voluntary. Canada regards management of natural reactivity as a public health issue that needs to be supervised by the local governments.

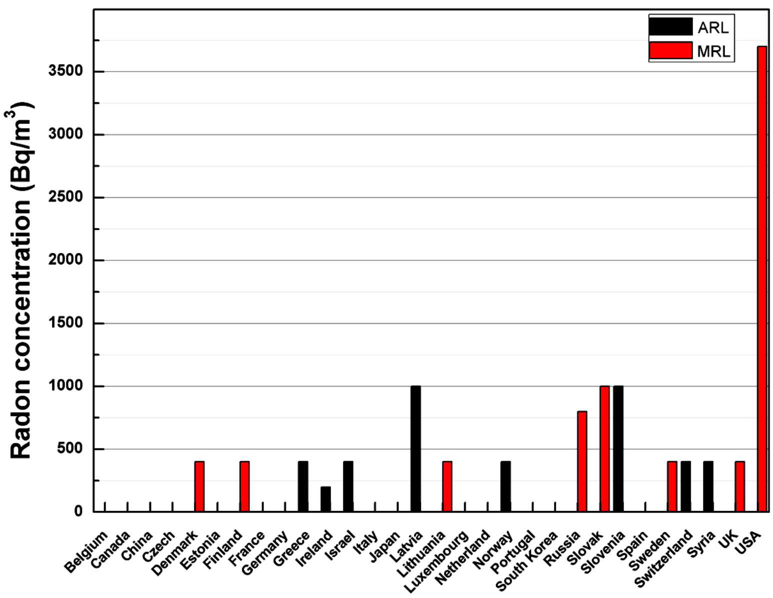

Figure 1. Radon guidelines of dwellings.

Workplaces

In the Radiation Protection 88 report, the EC recommended the guideline for radon in workplaces where the average radon gas concentration should be set in the range of 500-1,000 Bq/m^3. This is based on 2,000 h of occupational exposure per year or an equilibrium constant of approximately 0.4 [15]. A survey of 16 EU countries revealed that approximately 75% of workplaces are using

ARLs and MRLs of 400 Bq/m³ or less as the radon guideline for workers (figure 2). Austria, Greece, Norway and Germany have set 400 Bq/m³ as the ARL, whereas Denmark, Sweden and Finland have set 400 Bq/m³ as the MRL. However, some countries have stricter guidelines for new workplaces. For example, Austria, Ireland, Greece and Sweden have set 200 Bq/m³ as the guideline for new workplaces. The guidelines vary by country, but most Eastern European countries regulate radon levels in the range of 400-1,500 Bq/m³, where the upper limit of 1,500 Bq/m³ is the radon reference level in air for workers, as recommended by the ICRP in 2007. In conformance with the standard recommended by the U.S. Nuclear Regulatory Commission (U.S. NRC), the U.S. Occupational Safety and Health Administration (OSHA) has set 3,700 Bq/m³ as the average concentration for 7 consecutive days or 40 hours per week as the permissible exposure limit (PEL) of radon in workplaces [16]. Canada has set the limit as 400 Bq/m³ as followed in the EU. These two countries have legally mandated the MRL.

On the other hand, Japan has no radon guideline for workplaces. Australia and Israel recommend 400 Bq/m³ as the guideline for workplaces. Most EU countries supervise not only compliance with recommendations and orders, but also compliance with laws for radon in workplaces as well as in dwellings. In Denmark and Finland, national radiological protection agencies are designated as regulatory institutions with supervisory responsibility for compliance with radon regulations. In Sweden, the National Board of Occupational Safety and Health establishes regulations and local governments supervise industrial safety and health. In Switzerland, the Swiss National Accident Insurance Organization (Suva) supervises compliance with regulations. Likewise, in most Eastern European countries, the government supervises compliance with laws and recommendations. The radon management programmes of the USA are mostly voluntary, but they are different for each state. The workplace standards are managed by the OSHA, the Mine Safety and Health Administration (MSHA) and the Department of Energy (DOE). In Norway and Canada, local governments supervise and manage radon-related regulations as part of the management of natural radioactive materials. The U.S. Environmental Protection Agency (EPA) has general responsibility for radon management such as spreading awareness among the public regarding radon or promoting radon protection measures for dwellings [13]. Among the European countries, France, Finland, Germany, Norway and Ireland have protocols for measuring radon in workplaces. In Asia, Israel has measurement guidelines for radon management.

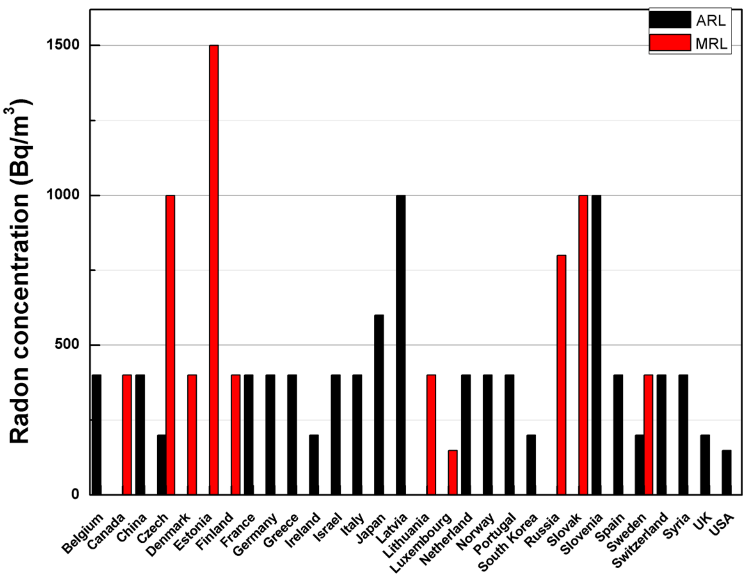

Figure 2. Radon guidelines of workplaces.

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DISCUSSION

The study results show that all countries included in this study have recommended or regulated the radon guidelines in the range of 148-400 Bq/m^3 for dwellings and public-use facilities except for Eastern Europe countries, and 200-1,000 Bq/m^3 for workplaces except for USA and Estonia. Thus, most countries have set guidelines separately for dwellings and workplaces. The guidelines are set based on 7,000 h of exposure time for the general public, and 2,000 h for workers [17]. The PEL of the OSHA is based on a weighted average exposure of 8 h, but the maximum permissible concentration (MPC) of the NRC is based on 40 h per week [16]. The US NRC suggests 0.33 WL or 111 Bq/m^3 (30 pCi/L, equilibrium constant F=1.0) as the derived air concentration (DAC) for radon and radon daughter nuclides and 4 WLM as the annual limit of intake (ALI) for inhalation [18, 19]. Although the radon exposure standards of the OSHA are higher than that of other countries, it stipulates that if the business owner complies with the annual average exposure limit of 111 Bq/m^3 for workers, which is the NRC guideline, the OSHA can consider it as an allowable violation [20].

Furthermore, the American Conference of Governmental Industrial Hygienists (ACGIH) has set 4 WLM as the threshold limit value (TLV) for radon and radon daughter nuclides. This is equal to 20 mSv which is the average effective dose limit for 5 years of exposure to radiation [21]. The ICRP and UNSCEAR convert the radon concentration to radon dose to express the effects of radon on the human body. The dose limit of ionising radiation is different for the general public and workers. For the general public, the dose limit has been set considering the general influencing factors for dose evaluation, that is, habit data such as exposure path, spatial distribution of radionuclide, exposure time, and the appropriate dose coefficient. The dose limit is an individual upper limit that is set to control the sum of doses from all radiation sources and actions in a planned exposure situation, and serves as the last defence when the radiation protection optimisation fails. The ICRP recommends that in probabilistic individual dose evaluations for setting the standard for the general public, the representative person should be defined in such a manner that the probability that a random person selected from the group is exposed to a greater dose than the representative person is smaller than 5%. The recommended dose limit for exposure in the case of the general public in a planned exposure situation is 1 mSv in annual effective dose per year. The dose limit for exposure in the case of workers is set as the effective dose of 20 mSv per year (100 mSv for 5 years) averaged for 5 years, where the effective dose in any one year does not exceed 50 mSv [22]. In general, the reference level (dose constraint value) for workers is set by the 'operator (business owner)' within the dose limit, and the reference level for the general public is set by the 'regulatory agency'.

The relative risk of unit exposure for lung cancer is 1.08, 1.11, and 1.13 per 100 Bq/m^3 in Europe, North America, and China, respectively [23]. In an integrated analysis in Europe, the odds ratio per 100 Bq/m^3 for lifetime non-smokers was 1.11 (95%, CI 1.00-1.28). In an integrated analysis in the USA, the odds ratio of non-smokers was approximately the same (1.10), but was not significant (95%, CI 0.91-1.42). According to the UNSCEAR 2006 report, when a patient group and a control group with precise individual cumulative radiation exposure valuations were analysed intensively, the linear dose-reaction gradient was 1.11 per 100 Bq/m^3 [23]. Thus, a cohort study on miners and a case-control study on radon exposure of dwellings arrived at the conclusion that there was clear evidence about radon causing lung cancer, but that the evidence for the existence of excessive risk for solid cancers or leukaemia related to radon exposure was weak.

The occupational exposure concentration of 1 Bq/m^3 as an hourly equilibrium equivalent concentration (EEC) for radon and radon daughter nuclides is equal to a committed effective dose of 8 nSv, as recommended by ICRP 115 [24]. In the case of thoron (^{220}Rn), it is equal to 36 nSv. Therefore, an effective dose of 20 mSv is equal to 4 WLM, 14 mJ·h/m^3 or 2.5×10^6 Bq·h/m^3 for radon. The value converted to Bq/m^3, which is the unit for radon concentration in air, is 3,000 Bq/m^3 for an annual working time of 2,000 h, equilibrium constant of 0.4, and dose conversion factor of 8 nSv. According to the standards defined by the UNSCEAR, an effective dose of 20 mSv equals 2,700 Bq/m^3 whereas it equals 1,500 Bq/m^3 according to the National Council for Radiation Protection (NCRP) standards. The reference level of 1,000 Bq/m^3 for workplaces recommended by ICRP 103 (25) corresponds to approximately 6-14 mSv/y as the range of estimated effective dose. This includes 10 mSv/y, which is the target value for reducing occupational exposure. However, one limitation in the consideration of the radon guidelines for workplaces in each country was that the inclusion of underground workplaces or industrial plants that handle radioactive materials could not be clearly distinguished because they differed by country.

CONCLUSION

The results of analysing the dose conversion factor for radon based on the annual effective dose showed that the ARL of 148 Bq/ m^3 of radon for dwellings was higher than the annual dose limit of 1 mSv for the general public, and the reference level of 1,000 Bq/m^3 of radon for workplaces was lower than the annual dose limit of 20 mSv for radiation workers. Although studies on radon are being conducted globally, sufficient research is lacking, and com prehensive, systematised academic studies are scarce. Thus, basic studies on radon reduction and evaluation technologies for indoor environment are urgently needed. Additional review of whether the targeted reduction in the level of radon should be reduced further can be decided through accumulation of research data. When the targeted reduction is further lowered, the exposure standards should be lowered as well. In conclusion, it is preferable to set the radon exposure standard for dwellings and workplaces as 148 Bq/m^3, which is the standard recommended by the U.S. EPA, and the exposure standard for workers in workplaces with high risk of radon exposure as between 400 Bq/m^3, which is the exposure standard adopted in most EU countries, and 1,000 Bq/m^3, which is the reference level set by the ICRP.

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