http://dx.doi.org/10.17946/JRST.2021.44.6.671
Journal of Radiological Science and Technology, 44(6), 671-677
ISSN 2384-1168(On-line) ISSN 2288-3509(Print)

<원저>

Radon Hazard Review of Spilled Groundwater and Tap Water in Incheon Metropolitan City Subway Station

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인천광역시 지하철 역사 내 지하수 및 수돗물의 라돈 위해성 검토

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Abstract Interest in the everyday hazards of radon has recently increased as such, this study attempted to examine the dangers of radon in spilled groundwater by comparing the radon concentrations of the drained groundwater and tap water used in recirculating systems in Incheon Subway restrooms. At five stations of Incheon Subway Line 1 and three stations of Line 2, drained groundwater is recirculated and used in restrooms for toilet flushing. Stations restroom tap water for hand washing that used as a control and the measured values of each were compared. With the cooperation of Incheon Transportation Corporation, samples of spilled groundwater and tap water were collected sealed to prevent contact with the air, and a DURRIDGE RAD7 was used as the experimental equipment. The collected samples were subjected to radial equilibration for approximately 3.5 h, at which the radon concentration reached its maximum, and then calculated as 10 measurements using the RAD7 underwater radon measurement mode. In all eight stations, the radon concentration in tap water was lower than the recommended amount. However, in an average of 7 out of the eight stations, the radon concentration in the effluent groundwater was 100 times higher than that in tap water. Since high radon concentrations in groundwater runoff can be harmful to humans, and there is no accurate standard for radon concentrations in domestic water, it is necessary to continuously monitor radon in water and prepare a guidance of recommended values.

Key Words: Radon, Groundwater, Tap water, Subway station, Effective dose
중심 단어: 라돈, 지하수, 수돗물, 지하철역, 유효선량

Ⅰ. Introduction

Radon(^{222}Rn) is one of the uranium series that converts to lead(^{206}Pb) using the natural radioactive element heavy uranium(^{238}U) that occurs as its progenitor is released. It is a colorless, odorless, tasteless inert gas, and it is present in the air, soil, cement, groundwater, and construction materials[1]. The United States Environmental Protection Agency defines radon as the second highest cause of lung cancer after

We thank the officials of Incheon Transportation Corporation for allowing sample collection for this study.
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Received 11 November 2021; Revised 7 December 2021; Accepted 13 December 2021

smoking[2]. This study said the ingestion of water with high radon content has been reported in cases of gastrointestinal damage and cancer[3]. In other words, the harmfulness of radon has been reported worldwide[4], so it is a reality that we are focusing on finding the source[5].

Radon inflow into groundwater is 0.2 $pCi \cdot L^{-1}$, and the average radon concentration in indoor air is 1 $pCi \cdot L^{-1}$, meaning that approximately one-fifth of indoor air is made up of radon, which is a significant portion. This is why measuring the radon concentration in water is just as important as measuring the radon concentration in the air[6]. There are several types of groundwater that leak into the soil during the construction and use of structures. Advance research of the Incheon area, revealed that a total of 10,699 $m^3 \cdot d^{-1}$ occurred in 17 places, including soccer stadiums, department stores, and subway stations.

From among these, approximately 2,705 $m^3 \cdot d^{-1}$ of groundwater is discharged from subway stations, accounting for more than 20% of radon leakage[7]. To minimize problems, such as the depletion of nearby water sources and subsidence significant groundwater outflow, the Incheon local government decided to increase resource circulation by recirculating groundwater in public facilities. In case of restrooms in five stations of Incheon Subway Line 1(Gyesan, Gyeongin National University Entrance, Bupyeong, Arts Center and Dongsu) and three stations on lines 2(Seo-gu Office, Seobu Women's Center and Juan) have used groundwater as water for toilet flushing[7]. Using spilled groundwater in this way is advantageous with respect to the soundness of resource circulation, but because spilled groundwater is leached from the crust, there is concern about the hazardous groundwater radon.

This study aims to measure the radioactive concentration of radon both in purified tap water and in drained groundwater that is recirculated in restrooms in Incheon Subway. Its hazardous effects will be observed and it will be used as basic data to monitoring.

II. Materials and Methods

1. Sample collection

The measurement targets are eight stations in Incheon Subway Lines 1 and 2 that use groundwater as Table 1. To determine the amount of radon discharged from the groundwater, the water recirculated and used in the same station and the tap water passed through the purification facility in the building were measured and compared.

Tap water was collected after flowing for 3 min. Spilled groundwater was collected by entering the control area with the help of the Incheon Transportation Corporation Mechanical Environment Equipment Team. To prevent radon from escaping into the air during collection, the sample was filled to overflow and sealed as tightly as possible with wrap and tape[8]. Since the half-life of radon is very short(up to 3.87 d), all samples were collected and measured on the same day to minimize the variability of the radon concentration[9].

Before being measured, the collected samples were stored in a measurement container and transferred. Radial equilibration was performed in consideration of the gaseous form of radon. For radial equilibrium, a stabilization time of approximately 3.5 h was applied in consideration of the degree radioactive decay. The estimated radon concentration was obtained using Equation 1 by measuring Po-218 and Po-214, which are

Table 1. Reused Water in Incheon Stations

Line	Station	Reuse($m^3 \cdot d^{-1}$)	Line	Station	Reuse($m^3 \cdot d^{-1}$)
Line 1	Bupyeong	21	Line 1	Dongsu	3
Line 1	Arts Center	31	Line 2	Seo-gu office	5
Line 1	Gyesan	15	Line 2	Juan	2
Line 1	Gyeongin University	8	Line 2	Community center	9

decaying nuclides. Because has no electrical properties due to the characteristics of the measuring to inert gas[10].

$$N_B = \frac{\lambda_A}{\lambda_B - \lambda_A} N_A (e^{-\lambda_A t} - e^{-\lambda_B t}) \qquad \text{Eq. (1)}$$

N_A : Nuclide A is the number of atoms after time t

N_B : Nuclide B is the number of atoms after time t

λ_A: Decay constant of A

λ_B: Decay constant of B

2. Radon measurement

RAD7 (DURRIDGE, USA), a piece of equipment capable of measuring radon gas concentration in outdoor air, indoor air, soil, and water, was used to obtain the measurements[11]. H_2O accessories suitable for measurement with a small amount of water by measurement range of 10 ~ 40,000 $pCi \cdot L^{-1}$ were used in this study[12]. The measuring device has a silicon detector in the form of a semiconductor, which measures α particle that occurs as a result of radon decay.

Since the sample was in the form of a liquid, it was studied with the aim of increasing the accuracy of the radon concentration measurement by removing the moisture in the bubble, blowing the bubble through the glass frit and passing it through a drying tube. The collected sample was confined to a 250 mL vial and the experiment was conducted by obtaining 10 measurements at five minute intervals using the Water-250 Protocol. Any radon particles that remained affecting the next measurement. Because radon is an inert gas, it is difficult to collect. This is why RAD7 measuring device, was used in this study using a pump, air is circulated to enable the continuous counting and measuring of radon particles.

Polonium(Po-218, 6.02 MeV and Po-214, 7.95 MeV) which are progeny released from radon were also counted and a method of inverse radon estimation was used based on this count.

3. Effective dose from Tap water and Spilled groundwater

The effective exposure dose of tap water and spilled groundwater was calculated using Equation 2.

$$E = D \times F \times R \times T \qquad \text{Eq. (2)}$$

E: Effective dose (mSv)

D: Dose conversion factor (mSv × $(Bq \cdot hr \cdot m^{-3})^{-1}$)

F: Equilibrium factor

R: Radon concentration ($Bq \cdot m^{-3}$)

T: Exposure time (hr)

For this exposure dose, the effective dose model suggested in the UNSCEAR 2000 report was used[13] the dose conversion factor was 9 × 10 $Bq \cdot m^{-3} \cdot h^{-1}$ and the equilibrium factor was applied to the indoor radon

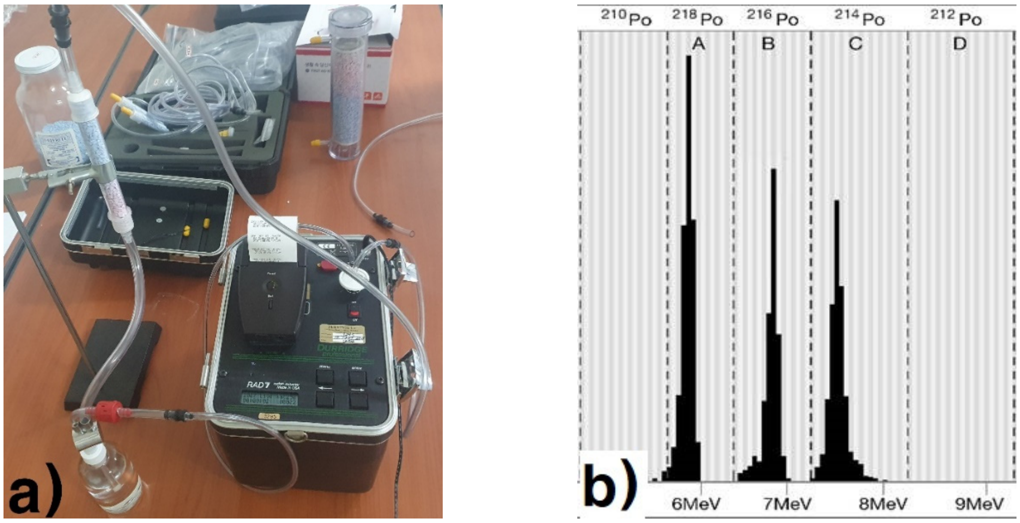

Fig. 1. Set-up measuring radon in water(a), and Po series spectrum(b)

value of 0.4. This was done because the equilibrium factor applied indoors is the typical standard for indoor radon regulation and reduction recommendation. The exposure time was assumed to be an average of 1 minute for men and 2 min for women based on the time spent in the restroom[14].

Ⅲ. Results

1. Radon concentration in Tap water and Spilled groundwater

Table 2 shows the results of the analysis of tap water and groundwater runoff the eight Incheon Subway stations. In tap water, which was purified once, the concentration of radon was found to be relatively lower than that in spilled groundwater. In tap water, the average radon concentration was $1.24 \times 10^2 \pm 1.10 \times 10^1$ Bq·m^{-3} and the minimum and maximum radon concentration were $9.30 \times 10^1 \pm 8.29 \times 10^0$ and $1.71 \times 10^2 \pm 1.47 \times 10^1$. In the case of groundwater, the minimum and maximum radon concentration were $1.71 \times 10^2 \pm 1.49 \times 10^1 \sim 7.94 \times 10^4 \pm 6.67 \times 10^3$ and average radon concentration was $2.56 \times 10^4 \pm 2.15 \times 10^3$.

2. Exposure dose from Tap water and Spilled groundwater

Based on the average value of the measurement results for each station, the average effective dose when exposed to tap water was 0.001 mSv(man) and 0.002 mSv(woman). In the case of groundwater, the minimum and maximum effective dose were 0.001~0.476 mSv(man) and 0.002 ~ 0.952 mSv(woman) as Table 3.

Ⅳ. Discussion

Base on the measurements, the average radon concentration in tap water 1.24×10^2 Bq·m^{-3}, which is within 1.48×10^2 Bq·m^{-3} the only recommended value for radon in indoor air[15]. Even in the history of the

Table 2. Results of Radon Measurement

Station	Type	Measurement & uncertainly (Bq·m^{-3})
Bupyeong	Tap water	$1.24 \times 10^2 \pm 1.11 \times 10^1$
	Groundwater	$3.89 \times 10^4 \pm 3.27 \times 10^3$ *
Arts Center	Tap water	$9.31 \times 10^1 \pm 8.21 \times 10^0$
	Groundwater	$2.93 \times 10^4 \pm 2.46 \times 10^3$ *
Gyesan	Tap water	$1.24 \times 10^2 \pm 1.10 \times 10^1$
	Groundwater	$7.94 \times 10^4 \pm 6.67 \times 10^3$ *
Gyeongin University	Tap water	$1.09 \times 10^2 \pm 9.54 \times 10^0$
	Groundwater	$1.38 \times 10^4 \pm 1.16 \times 10^3$ *
Dongsu	Tap water	$9.30 \times 10^1 \pm 8.29 \times 10^0$
	Groundwater	$3.58 \times 10^4 \pm 3.00 \times 10^3$ *
Seo-gu office	Tap water	$1.40 \times 10^2 \pm 1.24 \times 10^1$
	Groundwater	$2.43 \times 10^3 \pm 2.05 \times 10^2$ *
Juan	Tap water	$1.71 \times 10^2 \pm 1.47 \times 10^1$
	Groundwater	$5.19 \times 10^3 \pm 4.37 \times 10^2$ *
Community center	Tap water	$1.39 \times 10^2 \pm 1.24 \times 10^1$
	Groundwater	$1.71 \times 10^2 \pm 1.49 \times 10^1$ *
Mean ± Uncertainly	Tap water	$1.24 \times 10^2 \pm 1.10 \times 10^1$
	Groundwater	$2.56 \times 10^4 \pm 2.15 \times 10^3$ *

* Exceeding the recommended reference value

Table 3. Effective Dose of Water (Unit : mSv)

Station	Tap water		Groundwater	
	Man	Woman	Man	Woman
Bupyeong	0.001	0.001	0.233	0.467
Arts Center	0.001	0.001	0.176	0.351
Gyesan	0.001	0.001	0.476	0.952
Gyeongin University	0.001	0.001	0.083	0.166
Dongsu	0.001	0.001	0.215	0.429
Seo-gu office	0.001	0.002	0.015	0.029
Juan	0.001	0.002	0.031	0.062
Community center	0.001	0.002	0.001	0.002
Mean	0.001	0.002	0.154	0.307

maximum value, a resulting value of approximately 1.71 × 10^2 Bq·m^{-3} is within the uncertainly range.

However, in the case of groundwater, the average concentration was 2.56 × 10^4 Bq·m^{-3}, indicating that all eight stations exceeded the standard recommended value. In the case of the history where the maximum value came out, even 7.94 × 10^4 Bq·m^{-3} was detected which is approximately 100 times higher than the standard recommended value[14]. When compared with the radon radiation level of groundwater investigated by the National Institute of Environmental Research for 10 years, there were some areas where a maximum of 8.00 × 10^2 Bq·m^{-3} or more was detected[16]. In the case of groundwater used in this study, it was found that the effect of radon on the human body cannot be ignored if water containing radon is continuously used.

According to the measurements, there was 1.71 × 10^2 Bq·m^{-3} radon in groundwater from one station, which was approximately 10 times lower than the radon concentration in groundwater from other stations. It seems to the collected sample contained carbonic acid. Based on the average value of the measurement results for each station, the effective dose when exposed to tap water was 0.001 mSv. It was confirmed that this dose has little effect on the human body. However, when sustainedly exposed to groundwater spills, the exposure dose was an average of 0.15 mSv for men and 0.31 mSv for women. It was confirmed that when a person uses these restrooms continuously, the negative effect is not negligible. In South Korea, the concentration of radon in indoor air must be below 1.48 × 10^2 Bq·m^{-3} (WHO recommendation is less than 1.00 × 10^2 Bq·m^{-3}) only for multi−use facilities and new apartment complexes with 100 or more units according to the indoor air quality recommendation[17,18]. But this restriction only applies to radon in indoor air not radon in groundwater or soil. Therefore, in the case of leachate recirculated in subway stations, the maximum is 7.94 × 10^4 Bq·m^{-3}, which is commonly used around life with respect to recycling of resources. Thus, it is necessary to place restrictions on recirculated water. Currently, the concentration of radon in indoor air has only just begun to be regulated. Even though reduction facilities are being installed and continuous monitoring is being conducted, sufficient research on measures to reduce radon and to monitor drinking water and water quality has not been conducted[19].

Radon's hazardous effects on the human body are widely known. However, unnecessary expenses and misunderstandings due to public's indiscriminate fear of radon must also be avoided. To mitigate these risks, sufficient research, precise regulation and reduction measures will need to be carried out and determined. In the United States, the standard of radon concentration in drinking water that includes groundwater is less than 4,000 pCi·L^{-1}[20]. In South Korea, the Drinking Water Management Act and the notification on the operation of monitoring items for drinking water quality are applied to water that includes groundwater. However, this act does not address radon regulating guidance it simply states that water quality standards of international health organizations or advanced countries may be included. As such, there is no exact standard for regulating the concentration of radon in water. Thus, such a standard must be established. For example, since radon is typically in the form of a gas, the exposure dose can be minimized if aeration is well used. It must be urgently prepared to reduce the exposure dose to radon, a representative nuclide of natural radioactive materials as well as artificial radioactive materials.

Ⅴ. Conclusions

In this study, the radon concentrations of tap water and recirculated drained groundwater in eight stations of the Incheon Subway stations were reviewed, as were the potential hazards of these concentrations.

The average concentrations of radon in tap water was 1.24×10^2 Bq·m^{-3} which is within the recommended standard. However, in the case of spilled groundwater, the average concentration was 2.56×10^4 Bq·m^{-3}, which exceeds the recommended standard.

Based on the above results, the effective dose was calculated, and it was confirmed that tap water contains an average of 0.001 mSv radon, which has little effect on the human body. However, spilled groundwater contains an average of 0.15 mSv for men and 0.31 mSv for women which confirms that the hazard is not negligible.

The findings of this study can be used as basic data to provide a cornerstone for radon concentration standards and management measures in water. It is expected that continuous research on this topic will be needed.

REFERENCES

[1] Pervin S, Yeasmin S, Ferdous J, Begum A. A Study of Radon Concentration in Tap Water of Dhaka City. J Environ Pollut Manag. 2018;1(2):1-7.

[2] United States Environmental Protection Agency. National primary drinking water regulations; radon-222. Federal Register. 1999;64(211):59246-378. [cited 2021 Nov 10]. Available from: https://www.federalregister.gov/documents/1999/11/02/99-27741/national-primary-drinking-water-regulations-radon-222.

[3] Tirmarche M, Harrison JD, Laurier D, Paquet F, Balanchardon E, Marsh JW. Lung Cancer Risk from Radon and Progeny and statement on radon. Annals of ICRP. 2010;40(1):1-64.

[4] Lee SR, Lee SB, Kim JY, Kim JM, Bang YJ, Lee DS, et al.: Analysis of Radioactivity Concentrations in Cigarette Smoke and Tobacco Risk Assessment. Journal of Radiological Science and Technology. 2021;44(5):489-94.

[5] El-Araby E, Salman K, Mubarak F. Human Risk Due to Radon and Heavy Metals in Soil. Iran J Public Health. 2021;50(8):1624-34.

[6] Jeong SP, Jae HG, Chon HT. A Study on the Development of Testing Method to Measure Radon Concentration in Groundwater. Journal of the Korean Society of Mineral and Energy Resources Engineers. 2006;43(1):25-33.

[7] Incheon City. Incheon Metropolitan City Groundwater Management Plan. Incheon Metropolitan; 2017. [cited 2021 Nov 10]. Available from: City. http://announce.incheon.go.kr/citynet/jsp/cmm/attach/download.jsp?mode=download&fid=%238a10b67decda04cbee2a50af61457cb85776ca234b6d539fc461e20984c4472e&index=1&other=%23f4b42464d48b2be3d3a8f834d583531e21092d324a7e3e74c661d416cb8d8bed28e5269c4dc51117bd75fa5ff8a1f5ba.

[8] Kurnaz A, Atıf Cetiner M. Exposure assessment of the radon in residential tap water in Kastamonu. International Journal of Radiation Research. 2016; 14(3):245-50.

[9] Cook PG, Herczeg AL. Environmental Tracers in Subsurface Hydrology. Springer, Boston, MA; 2000. DOI: https://doi.org/10.1007/978-1-4615-4557-6_6

[10] KS A ISO 18589-3. Korean Agency for Technology and Standards, Measurement of radioactivity in the environment-Soil-Part 3: Measurement of gamma

−emitting radionuclides. 2012. [cited 2021 Nov 10]. Available from: https://standard.go.kr/KSCI/standardIntro/getStandardSearchList.do.

[11] DURRIDGE Company Inc. RAD H2O Radon in Water Accessory for the RAD7 User Manual. 2000. [cited 2021 Nov 10]. Available from: https://durridge.com/documentation/RAD%20H2O%20Manual.pdf.

[12] Malik MFI, Rabaiee NA, Jaafar MS. Determination Of Radon Concentration In Water Using RAD7 With RAD H2O Accessories. AIP Conference Proceedings. 2015;1657(1):1−5.

[13] UN Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation / United Nations Scientific Committee on the Effects of Atomic Radiation. 2000. [cited 2021 Nov 10]. Available from: https://digitallibrary.un.org/record/422833.

[14] Kim Y. Busan Metropolital city office of education 2020−144 (2020). 2020 Busan Metropolitan Office of Education Student Toilet Use Status Investigation; 2020. [cited 2021 Nov 10]. Available from: https://www.pen.go.kr/board/view.pen?boardId=BBS_5000043&menuCd=DOM_000000602016000000&paging=ok&startPage=1&dataSid=5743449.

[15] Ministry of Environment. Enforcement rules of the Indoor air quality management. 2021. [cited 2021 Nov 10]. Available from: https://www.law.go.kr/LSW/lsInfoP.do?efYd=20210611&lsiSeq=233143.

[16] Kang CS. A place with a high level of groundwater radiation...Southeastern Gyeonggi−do and Daejeon Chungbuk? The JoongAng. [cited 2013 May 29]. Available from: https://www.joongang.co.kr/article/11650459

[17] Korea Ministry of Government Legislation. Act of the Ministry of Environment No.918, 2021. Enforcement rules of the Indoor air quality management. [cited 2021 Nov 10]. Available from: https://www.law.go.kr/lsInfoP.do?lsId=008375#0000.

[18] WHO handbook on indoor radon: A public health perspecitve. Handbook. 2009. [cited 2021 Nov 10]. Available from: C:/Users/GC/Downloads/9789241547673_eng.pdf.

[19] Jo J, Lee S, Nam J, Noh E, Beak H, Lee Y, et al. Evaluation of Radioactive Substance and Measurement of Harmfulness in Drinking Water. Journal of Radiological Science and Technology. 2021;44(3):247−52.

[20] United States Environmental Protection Agency. Basic Information about Radon in Drinking Water. 1996. [cited 2021 Nov 10]. Available from: https://archive.epa.gov/water/archive/web/html/basicinformation−2.html.

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