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Towards Quantitative Assessment of Human Exposures to Indoor Radon Pollution from Groundwater

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Abstract

A report by the national research council in the United States suggested that many lung cancer deaths each year be associated with breathing radon in indoor air. Most of the indoor radon comes directly from soil beneath the basement or foundations. Recently, radon released from groundwater is found to contribute to the total inhalation risk from indoor air. This study presents the quantitative assessment of human exposures to radon released from the groundwater into indoor air. At first, a three-compartment model is developed to describe the transfer and distribution of radon released from groundwater in a house through showering, washing clothes, and flushing toilets. Then, to estimate a daily human exposure through inhalation of such radon for an adult, a physiologically-based pharmacokinetic (PBPK) model is developed. The use of a PBPK model for the inhaled radon could provide useful information regarding the distribution of radon among the organs of the human body. Indoor exposure patterns as input to the PBPK model are a more realistic situation associated with indoor radon pollution generated from a three-compartment model describing volatilization of radon from domestic water into household air. Combining the two models for inhaled radon in indoor air can be used to estimate a quantitative human exposure through the inhalation of indoor radon for adults based on two sets of exposure scenarios. The results obtained from the present study would help increase the quantitative understanding of risk assessment issues associated with the indoor radon released from groundwater.

Key words : Indoor radon pollution, Internal dose assessment, A PBPK model

1. INTRODUCTION

Radiation is a natural part of the environment in which we live. All people receive exposure from naturally occurring radioactivity in soil, air and food. The largest fraction of the natural radiation exposure in humans comes from a radioactive gas, radon. Radon is emitted from uranium, a naturally occurring mineral in rocks and soil; thus, radon is present virtually everywhere on the earth. Thus, low level of radon are present in the air we breathe. A recent report by the national research council (1999) in the United States estimated that between 3,000 and 32,000 lung cancer deaths each year are associated with breathing radon in indoor air. Most of the radon that enters a building comes directly from soil that is in contact with or beneath the basement or foundations. Radon is also found in well water and will enter a home whenever this water is used. During the activities in a house such

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as showering, washing clothes, and flushing toilets, radon is released from the water and mixed with the indoor air. Thus, radon released from groundwater contributes to the total inhalation risk from indoor air. Approximately half of the drinking water in the United States comes from groundwater. In Korea, a drinking water is known to be supplied by surface water. It is expected that the supply of drinking water will be limited soon and finally replaced by the groundwater due to the shortage of surface water. Surface water usually contains a low concentration of dissolved radon. However, water from groundwater systems can have relatively high levels of dissolved radon via migration of radon gas in the soil and/or rock. Some area are known to contain a radon concentration of 10,000 Bq/L or more in the United States. Because radon is easily released by agitation in water, many uses of water release radon into the indoor air, which contributes to the total indoor airborne radon concentration. Hence, radon has been identified as a public-health concern when presented in drinking water. In this case, such human risks associated with indoor radon exposures from the groundwater should be evaluated.

This study focuses on the quantitative human exposures to radon in indoor air released from a groundwater. Fig. 1 shows the radon exposure pathway considered in this study. First of all, underlying assumptions and limitations in the study are described as follows:

• The study assumes conservative human exposures from indoor radon pollution released from groundwater. In other word, this study considers "upper bound" exposures by assigning conservative values to the model parameters. Hence, it may not be relevant to realistic exposure assessments associated with indoor radon pollution.

• Predictions of indoor respiratory human exposure to radon are made for a normal 70-kg American male under the sets of conservative indoor exposure scenarios since considerably less information is available regarding physiological data in other age groups.

• A large degree of uncertainty exists in parameters used in mathematical models and it is difficult to estimate some parameters at this time. Models themselves will not remove all of the uncertainty in an analysis. However, the uncertainties in models could be quantified performing by an uncertainty analysis in further research.

The water supply containing radon from groundwater can contribute to increase indoor radon concentrations. In order to describe such transfer and distribution of radon released from groundwater in a house through showering, washing clothes, and flushing toilets, at first, a three compartment model is developed. Based on the model, daily radon concentration profiles for each compartment in the house are calculated.

For the quantitative assessment of a daily human exposure through the inhalation of such radon for an adult, a physiologically-based pharmacokinetic (PBPK) model is developed. The PBPK model are used increasingly in health risk assessment for several toxic chemicals. In this case, the use of a PBPK model for the inhaled radon are expected to provide useful information regarding the distribution of radon among the organs of the human body. Indoor exposure patterns as input to the PBPK model are a more realistic situation associated with indoor radon pollution generated from a three compartment model describing vol-

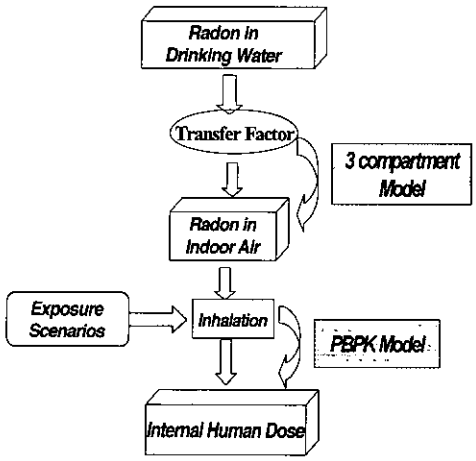

Fig. 1. Radon exposure pathway and methods used in the study.

atilization of radon from domestic water into household air. Combining the two models for inhaled radon in indoor air can be used to estimate a quantitative human exposure through inhalation of indoor radon for adults based on exposure scenario sets. The results obtained from the study would help increase the quantitative understanding of risk assessment issues associated with the indoor radon issue released from the groundwater.

2. METHOD

2. 1 Radon concentration in groundwater of Yusong

Han and Park (1996) measured the concentration of radon in the groundwater at Yusong. Table 1 shows the radon concentration in groundwater in the several sample sites located in Yusong. We performed a log-linear fitting based on their measurements and obtained a lognormal distribution which has a mean of 1106 pCi/L (40.9 Bq/L) and a 95th percentile of 8354 pCi/L (309.1 Bq/L). Fig. 2 is a log probability plot of the measurements and our fitting. The lognormal fitting shows a good agreement with the measurements by Han and Park. This study uses the mean obtained from the lognormal distribution as a reference value for the whole analysis.

Table 1. Radon concentrations in the groundwater samples at Yusong.

Location	Conc. (pCi/L)
Kyeongnam Apt.	1,420
KOSEF	3,460
Dangdae Spring	300
Samcheon Sports Park	720
Damsudae	670
KAIST #3 Hole	4,580
Eueun Spring	330
Hot Spring Park	2,400
Indong Hyundai Apt.	140
Chungnam University	1,430
KRISS	1,730
Hanul apt.	400
KBSI	10,310

2. 2 Development of three-compartment model for indoor radon distribution

The authors have already developed a three-compartment model that simulates the transfer and distribution of radon inside a home (Yu *et al.*, 2001). The

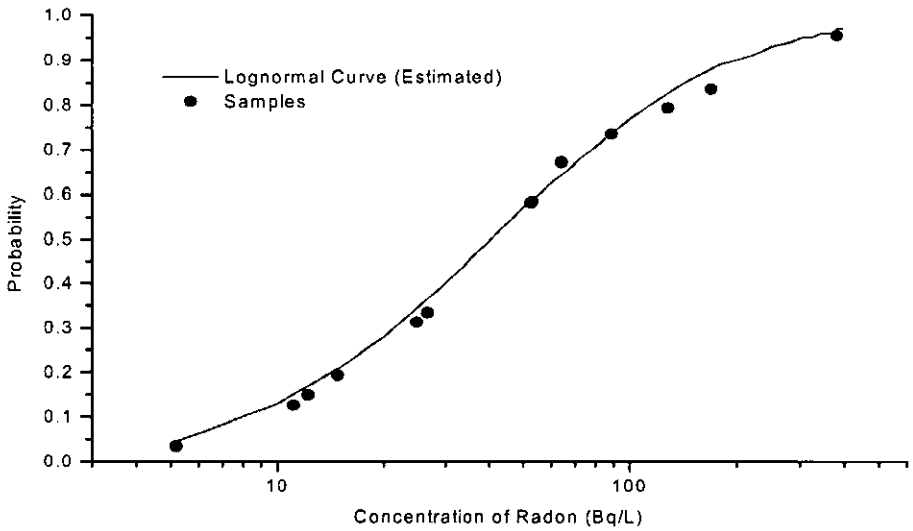

Fig. 2. Radon concentration profile: measured data vs. a fitted lognormal curve.

three compartments in this model was the shower/bath stall, the bathroom, and the remaining house-hold volume. Fig. 3 illustrates the major components of the model and shows the mass-flow pathways that are addressed in the model. The mass-balance differential equations for the three components were described below:

- Shower stall

$$V_s \frac{dC_s(t)}{dt} = Q_s(t) + q_{bs}C_b(t) - q_{sb}C_s(t) - \lambda_d V_s C_s(t) \quad (1)$$

- Bathroom

$$V_b \frac{dC_b(t)}{dt} = Q_b(t) + q_{sb}C_s(t) + q_{ab}C_a(t) - (q_{bs} + q_{bo} + q_{ba})C_b(t) - \lambda_d V_b C_b(t) \quad (2)$$

- Remainder of the house

$$V_a \frac{dC_a(t)}{dt} = Q_a(t) + q_{ba}C_b(t) - (q_{ab} + q_{ao})C_a(t) - \lambda_d V_a C_a(t) \quad (3)$$

In these equations, the C's, V's, Q's and q's refer to concentrations in Bq/L, sources in Bq/min, and air-exchange rates in L/min, respectively. The subscripts s, b, a are used to indicate the shower, bathroom, and remaining household compartments, respectively, while o denotes outside air. The q's are used to represent air-exchange rates, L/min, with the subscripts identifying the sources and end point of the transfer. In Fig. 3, R_s, R_b, and R_a are the residence times of air volumes in the three compartments and f_o is the fraction of air entering the bathroom that is exhausted directly to outside air by ventilation. The volumes of the compartments are obtained from the design values based the typical apartment of living area 100 m^2 (31 phyong) in Korea. The source terms Q_s, Q_b and Q_a are used to account for the input of radon from the use of groundwater in each respective compartment. The water consumption rate for shower and other activities such as cleaning are taken from a paper by Han (1995). The mass-transfer coefficient of radon at the air-water interface was obtained from a study performed by McKone (1987).

The detailed description regarding the development of compartment model and the selection of input parameters used in the model can be founded in the paper by Yu (2001).

2. 3 Development of the PBPK model

A PBPK (physiologically-based pharmacokinetic) model is described mathematically by a set of simultaneous differential equations which quantify the changing rate of the amount of a chemical within tissue groups. The tissue groups are simplified and idealized

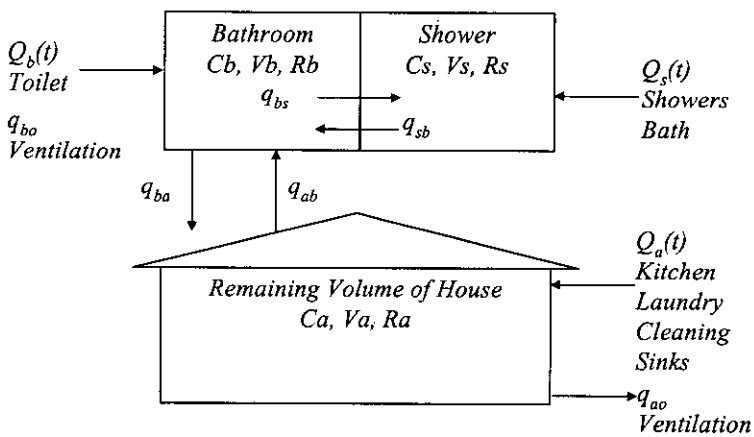

Fig. 3. A three-compartment Model for simulating the transfer of radon from groundwater to indoor air.

organs with respect to the actual anatomy and physiology of a test animal. Hence, they correspond either to specific, localized anatomic structures- liver, lung, kidney, etc.- or, to type of tissues- such as fat, muscle, etc.- that are distributed throughout the body. Tissue retention of compounds can be related to tissue/blood partition coefficients. The parameters specific to particular animals (tissue volumes, blood flow rates, physiological variables, etc.) in conjunction with the set of equations that comprises the physiological model, make it possible to simulate the way behavior changes with time. Hence the PBPK models provide a tool to understand the fate of chemicals in the body, and to relate exposure concentrations quantitatively to blood or tissue concentrations over a wide range of exposure concentrations.

The PBPK model for radon developed here (See Fig. 4) was based on the model mentioned in the report by NRC (1999). Briefly, the pulmonary uptake of a radon gas from indoor air occurs continuously so that alveolar concentration is in instantaneous equilibrium with arterial blood governed by the blood/air partition coefficient. The radon absorbed is distributed by the blood flow to the organs, where its transfer depends on its solubility in tissue relative to that in blood-the partition coefficient. Venous blood is pumped by the right side of the heart to the pulmonary region of the lung, where radon dissolved in blood exchanges with alveolar air and is exhaled.

The reference values for the total blood volume and cardiac output in an adult male are 5.3 L and 6.5 L/min, respectively (Leggett and William, 1995). The large arteries and veins contain 6 and 18% of the blood volume of the body, respectively. The distribution of cardiac output and tissue-to-blood partition coefficient for the various organs are given in Table 3. The masses and densities of the organs in the adult male are given in Table 4. The adult is assumed to breath 13.27

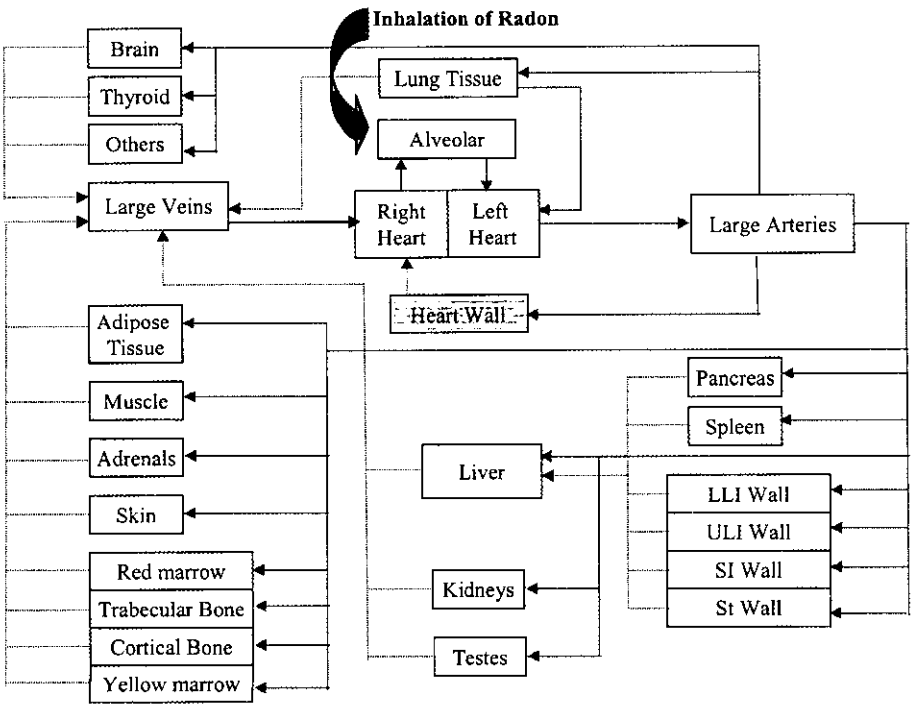

Fig. 4. Diagram of PBPK model used for the inhaled radon.

Table 2. Reference blood flow (% of cardiac output) and tissue-to-blood partition coefficients in PBPK model.

Tissue group	Fraction of cardiac flow (%)	Partition coefficient
stomach wall	1.0	0.7
small intestine wall	10.0	0.7
Upper large intestine wall	2.0	0.7
lower large intestine wall	2.0	0.7
pancreas	1.0	0.4
spleen	3.0	0.7
adrenals	0.3	0.7
brain	12.0	0.7
heart wall	4.0	0.5
liver	6.5	0.7
lung tissue	2.5	0.7
kidneys	19.0	0.66
muscle	17.0	0.36
red marrow	3.0	8.2
yellow marrow	3.0	8.2
trabecular bone	0.9	0.36
cortical bone	0.6	0.36
adipose tissue	5.0	11.2
skin	5.0	0.36
thyroid	1.5	0.7
testes	0.05	0.43
others	3.2	0.7

Table 3. Mass and density of organs in the adult male.

Tissue group	Mass (kg)	Density (kg/L)
stomach wall	0.15	1.05
small intestine wall	0.64	1.04
Upper large intestine wall	0.24	1.04
lower large intestine wall	0.16	1.04
pancreas	0.10	1.05
spleen	0.18	1.02
adrenals	0.014	1.03
brain	1.4	1.03
heart wall	0.33	1.03
liver	1.8	1.04
lung tissue	0.47	1.05
kidneys	0.31	1.05
muscle	28.0	1.04
red marrow	1.5	1.03
yellow marrow	1.5	0.98
trabecular bone	1.0	1.92
cortical bone	4.0	1.99
adipose tissue	12.5	0.92
skin	2.6	1.05
thyroid	0.02	1.05
testes	0.035	1.04
others	3.2	1.04

L/min for 16 hours per day while active and 7.375 L/min for 8 hours per day while resting or sleeping (USEPA, 1996).

3. RESULTS

3. 1 Radon concentrations in indoor air

Fig. 5 displays the calculated 24-h concentration profile for radon from the three compartment model. This figure illustrates that the concentration profile in all three compartments is driven by the source term in the shower stall, which begin at 7 a.m. After the peak concentration in the shower stall decays, the concentration in the shower, bathroom, and remaining household compartments becomes dependent on the other sources.

To calculate the daily average time-dependent concentration profile for human exposure, the following expression is used:

$$C_{in} = F_s C_s + F_b C_b + F_a C_a \quad (10)$$

in which C_{in} (Bq/L) is personal air concentration at time t and F_s, F_b, F_a are occupancy factors representing the probability that an individual is in the shower, bathroom, or remaining household, respectively, at time t.

A daily concentration profile of radon in personal air is illustrated in Fig. 6 for an individual associated with two scenarios of daily exposures: a base case and a worst case. The base case includes the following assumptions:

- Occupant spends 100% of his time in the house from 11 p.m. to 7 a.m.
- The bathroom is used for showers/baths from 7 a.m. to 8 a.m.
- Adult spends 10 min in the shower or bath.
- Adult leaves the home and goes to work between 8 a.m. and 7 p.m.
- Adult goes to sleep at 11 p.m.

The worst exposure case includes the above set of assumptions with the following modification:

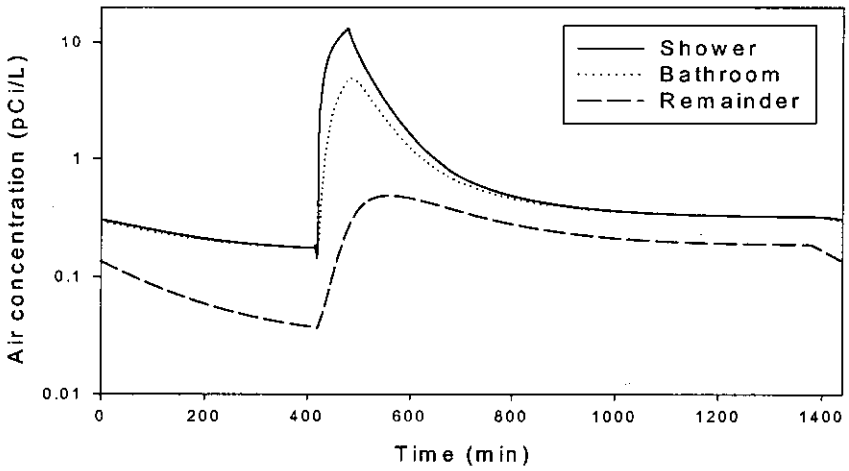

Fig. 5. Estimated 24-h concentration of radon in household compartment.

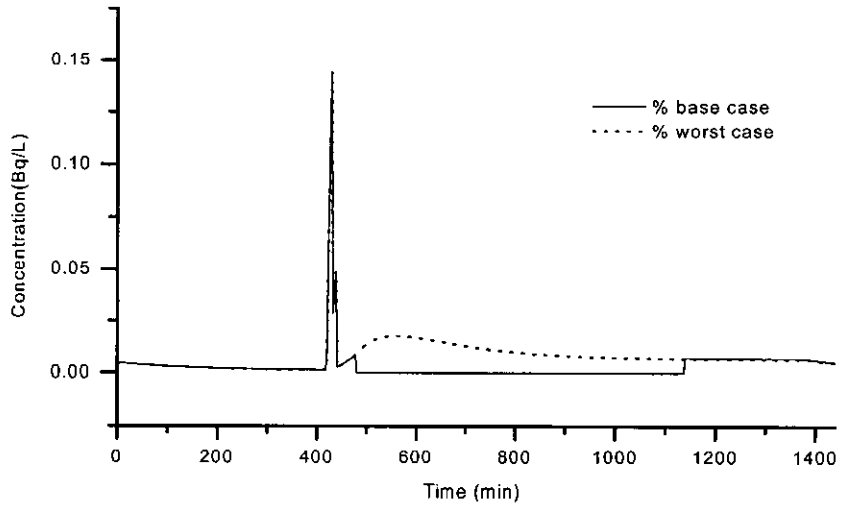

Fig. 6. Concentration profile of radon in personal air derived from three compartment model.

• Adult spends all of his time in the house.

3. 2 Internal dose assessment by the PBPK model

Based on the personal air concentration profile mentioned previously, we performed an internal dose assessment using the PBPK model. Since the lung tissue is a major target organ for radon inhalation, the kinetic behavior of radon in the lung tissue is evaluated in this study. Especially, the cumulative internal dose of lung tissue can be used for the estimating risk from inhaled radon. Fig. 7 shows the cumulative internal concentration of radon in the lung tissue associated with the two different exposure scenarios. The result shows that total dose in the lung tissue for the worst exposure case can be 3 times higher than that for the base exposure case.

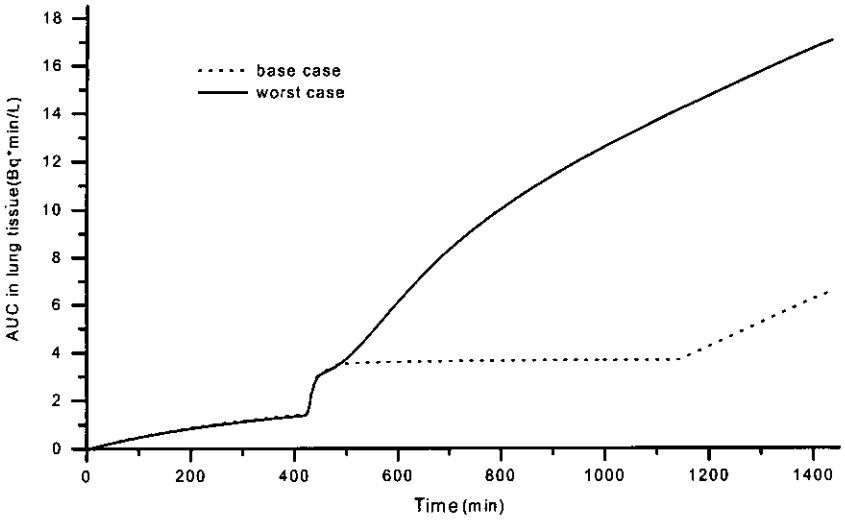

Fig. 7. Cumulated internal dose in the lung tissue derived by the PBPK model.

4. SUMMARY

This study presented the method of a quantitative human exposure assessments of radon released from the groundwater into indoor air. The three-compartment model was developed to describe the transfer and distribution of radon released from groundwater in a household through showering, washing clothes, and flushing toilets. The daily average personal concentration profile from indoor radon exposure was estimated for two exposure scenarios: a base case and worst case. The base case exposure scenario included the normal life style of an male adult in household in a day. On the other hand, the worst case assumed the maximum exposure for an male adult spending all his time in the house. Based on the daily concentration profile of radon in personal air, it is necessary to estimate a quantitative internal dose of a certain target organ through inhalation of a radon. A physiologically-based pharmacokinetic (PBPK) model was developed for this purpose. The PBPK model for the inhaled radon could provide useful information regarding the distribution of radon among several organs in a human body. The lung tissue is believed as a major target organ for a inhaled radon. Hence, the cumulative concentration of radon in lung tissues was evaluated based on the PBPK model. The result showed that the cumulative dose in lung tissues of the worst exposure case was up to 3 times higher than that of the base case.

As shown in this study, development of such mathematically-based models could be used to estimate a quantitative human exposure for inhaled radon in a indoor air released from groundwater. The results obtained from the study would help increase the quantitative understanding of risk assessment issues associated with the indoor radon released from groundwater.

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