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Characterization of environmental radiological parameters on dose coefficient - Realistic dosimetry compared with epidemiological dosimetry models

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ABSTRACT

Radiation exposure due to all-natural sources amounts to about 2.4 mSv per year. However, this amount might be changed to over 3 mSv y^{-1} according to the recently introduced ICRP radon dose coefficient factor. Previously, the radon contribution to the total dose from natural sources was about 1.2 mSv y^{-1}. However, after the latest introduced dose conversion factor by ICRP, this value could technically be increased to around 2 mSv y^{-1}. This paper attempts to address the following questions: (i) whether reducing radon concentration to the recommended level could address concerns about radiation exposure in underground workplaces, and (ii) the effects of the difference between the epidemiological dosimetry models and realistic dose estimation. The actual dose conversion factor (DCF) was calculated using measured annual average unattached and equilibrium factors, ranging from 16 ± 9 to 25 ± 10 mSv·WLM^{-1}. Then, the estimated inhalation dose, both from self-calculated DCF and the value reported by ICRP-137, was compared: 5.6 ± 0.7–7.6 ± 0.9 mSv y^{-1} and 3.3 ± 0.4–3.6 ± 0.5 mSv y^{-1}, respectively. It can be observed that exposure to a radon concentration lower than the recommended level does not guarantee a lower dose than the recommended value. The estimated dose was at least two times greater than the dose using pre-estimated values from epidemiological dosimetry models, specifically in this case study. Further experiments in different underground working environments, excluding caves, are needed for more precise observations. It might also be time to update the data regarding the dose contribution from natural radiation sources, as the radon contribution increased according to ICRP.

1. Introduction

On average, human radiation exposure due to all-natural sources amounts to about 2.4 mSv per year. However, this amount might change to over 3 mSv according to the recently introduced ICRP radon dose conversion factor [1]. In other words, previously, the radon contribution to the total dose from natural sources was about 1.2 mSv y^{-1}. However, after the latest dose conversion factor introduced by ICRP, this value could technically increase to around 2 mSv y^{-1} (reference: this study).

In the sixteenth century, there were indications of increased mortality from respiratory diseases among certain groups of underground miners, although there was no evidence linking the illnesses to radon concentration in the mines. In recent decades, several

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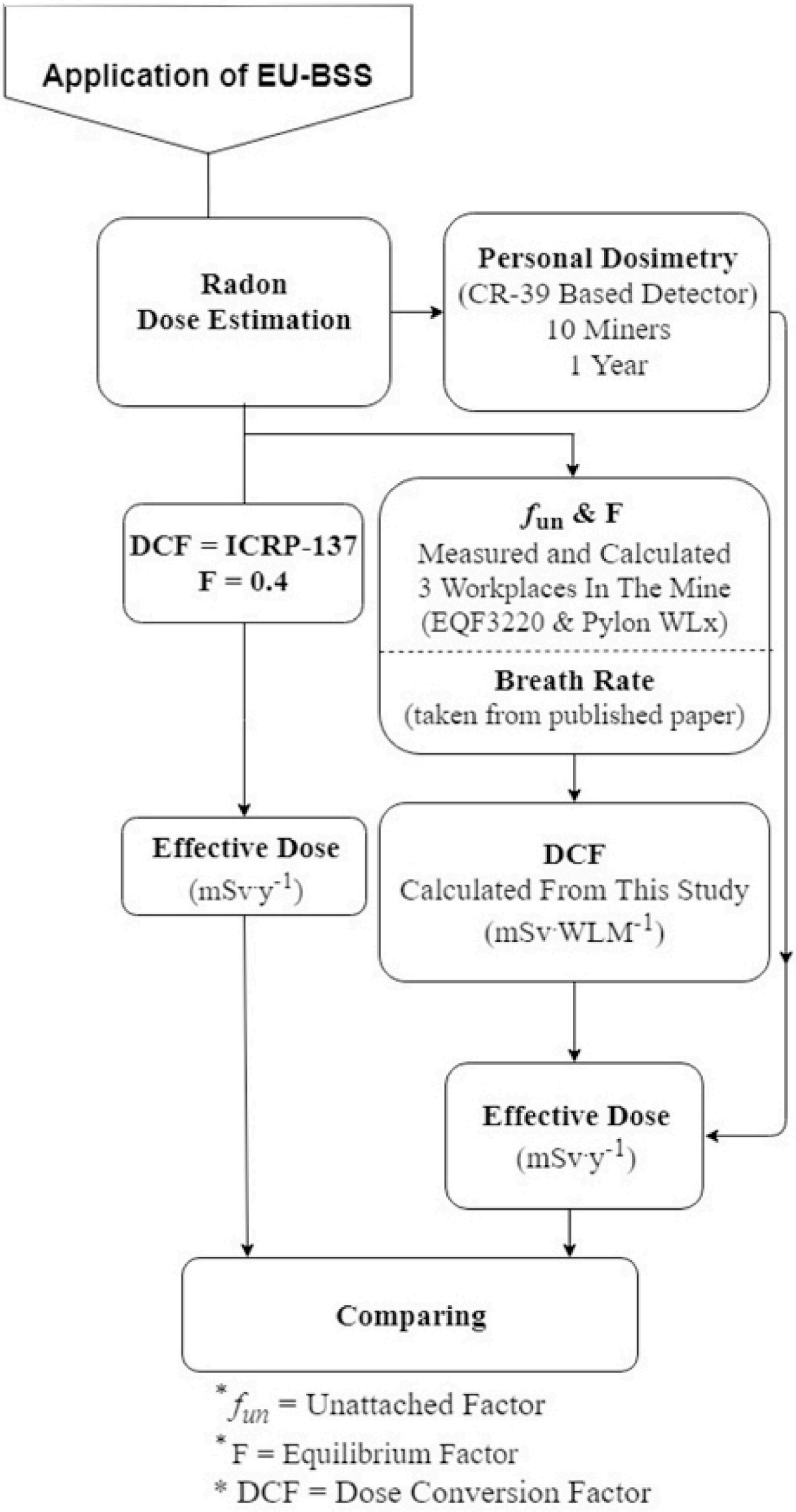

Fig. 1. Conceptual experiment design.

epidemiological studies have been conducted to identify potential risk factors associated with the development of irreversible occupational respiratory diseases, including silicosis and lung cancer, among underground excavation workers [2–9]. These studies have revealed that approximately 40% of lung cancer deaths in mines are attributable to exposure to radon progeny, accounting for 70% of lung cancer deaths in never-smokers and 39% of lung cancer deaths in smokers [10].

Radon itself poses no substantial health risk, as the dose directly from inhaled radon is low, whereas the dose is delivered by the short-lived decay products of radon [11]. There are two approaches to assessing the dose from radon and its decay products: (i) epidemiological dosimetry models (e.g., ICRP and USEPA); (ii) realistic dosimetry surveys. The outcomes may differ depending on the parameters applied during dose estimation, such as the attached/unattached fraction, equilibrium factor, and calculated dose conversion factor. Many studies in dose assessment rely on pre-calculated radiological parameters, including the equilibrium factor and dose coefficient. The equilibrium factor, an independent parameter, is calculated using the ratio of attached and unattached progeny. Radon progeny can be divided into two groups [1]: a fraction that becomes attached to existing aerosols in the atmosphere [2]; a fraction that remains in its original ionic or atomic form [12]. The ratio between ultrafine/unattached and attached particles is important as it is used to calculate the dose conversion factor (DCF). While a large portion of unattached progeny deposits in the respiratory tract, approximately 80% of attached radon progeny are expelled after each breath. The unattached activity constitutes about 10% of the total activity but contributes 50% of the total radiation dose. Ruzer conducted experiments on the correlation between the unattached fraction of radon decay products and the aerosol surface area [13].

Although pre-calculated equilibrium factors and dose conversion factors from epidemiological models are commonly used in dose assessment for simplicity and practicality, these values may differ from the actual values present in the investigated environment [14]. Various environmental conditions can influence the radon equilibrium factor, which represents the ratio of the concentrations of short-lived radon progeny to the concentration of radon gas. Some key factors that can impact the radon equilibrium factor include: (i) Ventilation rates, as ventilation rates can lead to increased air exchange, reducing the accumulation of short-lived radon progeny and resulting in a lower equilibrium factor. On the other hand, in poorly ventilated areas, the equilibrium factor tends to be higher as radon progeny have more time to accumulate and reach equilibrium with the radon gas; (ii) Aerosols and particulate matter, as the presence of aerosols and particulate matter in the air can affect the equilibrium factor. Aerosols can act as carriers for radon progeny, facilitating their transport and removal from the air, thereby reducing the equilibrium factor. Conversely, reduced aerosol levels or the presence of certain aerosol types can inhibit the removal of radon progeny, leading to a higher equilibrium factor; (iii) Humidity levels and temperature, as humidity levels can promote the condensation and deposition of radon progeny onto surfaces, and temperature can play an important role in air exchange.

Therefore, it's worth noting that these factors can interact with each other, and their influence on the equilibrium factor may vary depending on the specific environmental conditions and the characteristics of the radon source. Understanding and accounting for these environmental factors is crucial for accurate radon measurements and the proper assessment of associated health risks. To achieve precise dose estimation, it is necessary to calculate these values based on real measurements.

The DCF value directly links to the attachment process and the equilibrium between radon and its short-lived decay products. Breathing behavior and the size distribution of the decay products play an important role 15). Therefore, a realistic dose evaluation requires observing these independent radiological parameters.

In our previous publication, the dose was calculated based on the changes in the equilibrium factor, resulting in a range of 1 ± 1 to 6.2 ± 3 mSv per year in the same working environment. Further study was suggested to investigate the influence of the DCF. Therefore, this study intends to measure the influential radiological parameters on radon dose assessment and compare the influence of DCF (from ICRP, USEPA, and practically calculated values) on the dose value. An underground mine was selected as a case study for this investigation. Long-term radon concentration measurements and personal dosimetry were carried out, and the results have already been published [15,16]. The behavior of attached and unattached progeny was investigated during the experiment. Additionally, long-term personal dosimetry among the miners was conducted to determine the difference between the actual and recommended DCF on dose estimation. Fig. 1 shows the concept of the experiment.

2. Materials and methods

2.1. Radon exposure & dosimetry

Measuring occupational radon exposure can take several forms, including: 1) monitoring radon concentration in the area, or 2) using personal dosimeters. Measuring radon concentration is the most common method, as it is more convenient and easier to conduct (as is the case with EU-BSS). However, when a precise dose evaluation is required, personal dosimetry can be used to monitor workers' exposure to radon.

Exposure to radon and its airborne decay products express as Working Level Months, a unit of exposure to 1 WL for 170 h. In the absence of experimental data on the equilibrium between radon and its decay products, the USEPA recommended a pre-calculated value to estimate the annual radon exposure by following Equation (1) [17,18]:

$$WLM_a = C_{Rn}\left(\frac{F}{3700}\right)\ S\left(\frac{H_a}{170}\right) \qquad \text{[Eq.1.]}$$

where WLM_a is the annual exposure level to radon decay products, C_{Rn} is the average radon concentration (Bq·m^{-3}), F is the equilibrium factor, S is the factor of spending time in the workplace, and H_a is the total annual hours.

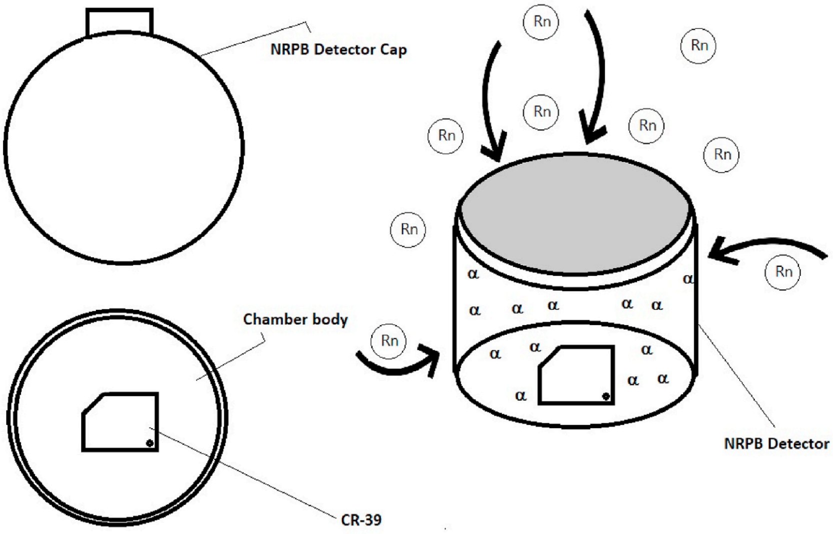

Fig. 2. CR-39 based NRPB personal dosimeter detectors.

Alpha track personal dosimeter detectors (PDD) were used to estimate the annual average Rn-222 exposure level. This study utilized a diffusion chamber-based dosimeter called the radon gas selective chamber NRPB, as shown in Fig. 2. The CR-39 based NRPB personal dosimeter detector consists of several key elements. The central component is the CR-39 detector, which is a type of solid-state nuclear track detector. When the dosimeter is exposed to radiation, the charged particles generated by the radiation interact with the CR-39 detector. These particles penetrate the detector and create tracks or etch pits in the material. The number and characteristics of these tracks provide information about the radiation dose received. After the exposure period, the CR-39 detector is chemically etched to enlarge the tracks and make them visible. This process involves immersing the detector in an etching solution that selectively removes the material surrounding the tracks, enhancing their visibility. The tracks can then be counted and analyzed to determine the radiation dose. Further details are extensively discussed in our previous publications [19–22].

2.2. *Determination of attached, unattached fraction & equilibrium factor*

The unattached fraction of radon progeny was determined using Equation (2):

$$f_{un} = \left(\frac{PAEC_{un}}{(PAEC_{att} + PAEC_{un})}\right) \qquad \text{[Eq.2.]}$$

where f_{un} is the unattached fraction, $PAEC_{un}$ is the potential alpha energy concentration ($PAEC$) of unattached radon progeny ($J \cdot m^{-3}$), and $PAEC_{att}$ is the potential alpha energy concentration of attached radon progeny ($J \cdot m^{-3}$).

The attached and unattached fractions of short-lived radon decay products were measured using an EQF3220 radon/thoron monitor (SARAD, Germany) equipped with high-end semiconductor radiation detectors and a built-in pump. The EQF3220 measurements are divided into categories as (i) detector filter: EEC and PAEC of the attached fraction of Rn-222 progeny; (ii) Detector screen: EEC and PAEC of the unattached fraction Rn-222 progeny. The relative error of measurements depends on the magnitude of the concentration of the radon and its progeny. The relative error was between 5% and 8%, with an average of 6% at concentrations above 1000 $Bq \cdot m^{-3}$; while it was about 14% (from 10% to 16%) in low concentrations (200–1000 $Bq \cdot m^{-3}$).

Then by using data from SARAD EQF3220, the equilibrium factor was calculated using Equation (3):

$$F = \left(\frac{EEC_{att} + EEC_{UN}}{C_{Rn}}\right) \qquad \text{[Eq.3.]}$$

where F is the equilibrium factor, C_{Rn} is radon concentrations, EEC_{att} and EEC_{un} are radon equilibrium equivalent concentrations for attached and unattached progeny, respectively.

Additionally, Pylon WLx (Radon Daughter Element Concentration Measuring) was used to measure simultaneously the radon working level and equilibrium equivalent concentration (EEC) that could be used to calculate the equilibrium factor (F) [15].

2.3. *Determination of attached, unattached fraction & equilibrium factor*

There are two approaches to assessing radiation doses from radon exposures: (i) using pre-calculated dose conversion coefficients derived from epidemiological models by ICRP or USEPA. The DCF value is directly influenced by factors such as breathing behavior,

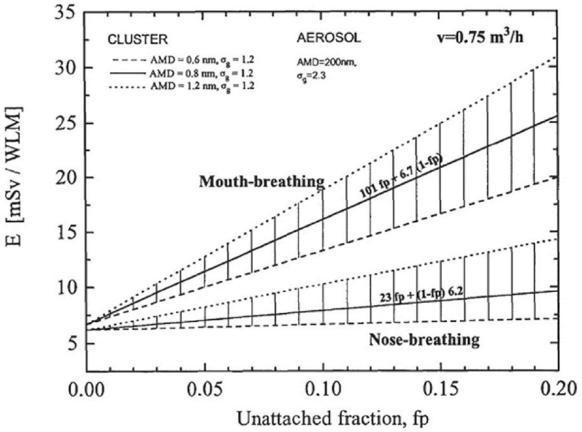

Fig. 3. Influence of the unattached fraction (fp) on the DCF (E) (Porstendörfer, 1996).

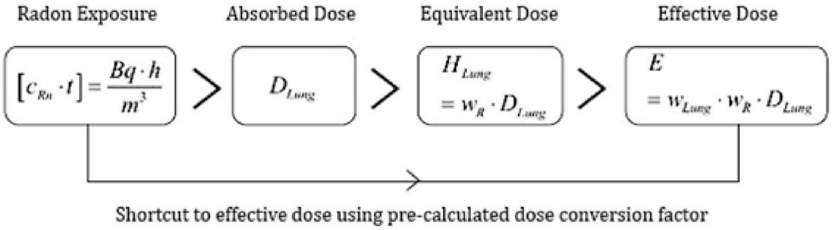

Fig. 4. The sequence of stages from radon exposure to inhalation dose.

the equilibrium ratio between radon and its decay products, and the attached/unattached fraction. Therefore, the estimated dose may be higher or lower than the actual dose. (ii) Using a dose conversion factor obtained through direct measurements in the field. The dose conversion factor can be calculated individually based on environmental radiological parameters and breathing behavior (refer to Fig. 3) using Equations (4) and (5) [23].

$$DCF_m = 101\, f_{un} + 6.7\,(1 - f_{un}) \quad \text{[Eq.4.]}$$

$$DCF_n = 23\, f_{un} + 6.2\,(1 - f_{un}) \quad \text{[Eq.5.]}$$

DCFm and DCFn are the dose conversion factors for mouth and nose breathing (mSv·WLM^{-1}), respectively.

According to Bennett et al., 2003, the breathing behavior of heavy physical male workers (e.g., miners) is a combination of 60% and 40% of mouth and nasal breathing, respectively. Therefore, the dose conversion factor can be calculated using Equation (6) for miners:

$$DCF_{mn} = 0.6\, DCF_m + 0.4\, DCF_n \quad \text{[Eq.6.]}$$

where DCF_{mn} is the dose conversion factor for combined breathing (mSv·WLM^{-1}).

This study used realistic and epidemiological models to calculate the dose conversion factor and comprehensively compare obtained values. Fig. 4 shows a schematic representation from radon exposure to the inhalation dose.

Where the lung absorbed dose (D_{Lung}) is determined by biokinetic models. The lung equivalent dose (H_{Lung}) and the inhalation dose (E) are obtained by the radiation weighting factor W_R (changed or unchanged) and the tissue weighting factor (W_{Lung}), respectively.

2.4. Estimation of effective dose

The annual effective dose from radon (mSv·y^{-1}) was estimated using the equation recommended by ICRP (Equation (7)) and the one suggested by WHO and USEPA (Equation (8)) [1,11,17]:

$$E_{ICRP} = DCF\,\left(1.57 \times 10^{-6}\right) \sum_i C_{Rn}\, F_i\, O_i \quad \text{[Eq.7.]}$$

$$E_{EPA} = C_{Rn}\left(\frac{F}{3700}\right)\left(\frac{T}{170}\right) DCF = WLM_a \times DCF \quad \text{[Eq.8.]}$$

where E is the annual effective dose (mSv·y^{-1}), T is the total hours in 1 year. C_{Rn} is the yearly average radon concentration (Bq·m^{-3}). F_i

Table 1
The Annual average of unattached factors in three working locations.

	Minimum	Maximum	Annual Mean
Location 1	0.07 ± 0.01	0.24 ± 0.03	0.15 ± 0.04
Location 2	0.21 ± 0.04	0.38 ± 0.05	0.3 ± 0.05
Location 3	0.18 ± 0.03	0.28 ± 0.05	0.21 ± 0.04
∑ Average	**0.21 ± 0.04**		

Table 2
The influence of the equilibrium factor on effective dose from our previous study.

Empty Cell	2013				2014			
Equilibrium Factor	0.2 ± 0.1[a]	0.35 ± 0.1[b]	0.4 ± 0.1[c]	0.55 ± 0.2[b]	0.2 ± 0.1[a]	0.35 ± 0.1[b]	0.4 ± 0.1[c]	0.55 ± 0.2[b]
Effective Dose (mSv year$-^{1}$) ICRP [1]	2.2 ± 1	3.8 ± 1	4.4 ± 1	6.1 ± 3	2.3 ± 1	3.9 ± 1	4.6 ± 2	6.2 ± 3
Effective Dose (mSv year^{-1}) UNSCEAR [25]	1 ± 1	1.8 ± 1	2 ± 1	2.8 ± 1	1.1 ± 1	1.8 ± 1	2.1 ± 1	2.9 ± 1

[a] Suggested equilibrium factor value for well-ventilated places such as mines (in our case, after ventilation development).
[b] Minimum and maximum equilibrium factor values come from our measurements.
[c] Suggested equilibrium factor value in the literature.

is the equilibrium factor, and O_i is the annual occupancy (h) in location i.

2.5. Calibration of devices

To determine the calibration factor of personal radon monitor detectors (NRPB CR-39 detector), a Genitron EV03209 calibration chamber, a PYLON RN 2000A radon emanation source and an AlphaGUARD PQ2000PRO radon monitor were used to calibrate the detectors. Detectors were exposed to a stable ^{222}Rn concentration for 6 days. The AlphaGUARD, as a reference instrument, was used to monitor the radon concentration in the barrel. The AlphaGUARD yearly contributes to intercomparison measurements and, every 2 years, sends it to a certified institute for calibration. Additionally, before this study and as an internal QA process, the AlphaGUARD was calibrated using a certified 210.5 L metal chamber (Genitron EV 03209) equipped with an electric fan to ensure internal homogenization. The homogenization of the gas inside the chamber was examined using 5 CR-39 placed at three different height levels. The standard deviation was calculated from 1% to 3% with an average of 1.5%). A certified radon source with 105.7 ± 0.42 kBq radium (Ra-226) (Pylon RN2000A, a passive radon gas source; Pylon Electronics Inc., Canada) supplied a known concentration of radon in the chamber. Then, the radon concentration, after decay constant correction, was compared with the radon reference to calculate the calibration factor (in the case of this instrument calibration factor was ~1). The device's background was measured using a radon-free chamber of about 5 ± 25% Bq·m^{-3}. Therefore, the detection threshold of the instrument was estimated to be 5 Bq·m^{-3}. The EQF3220 (SARAD, Germany) is periodically sent to the manufacturer in Germany for calibration. A loop system with a radon-free gas (nitrogen gas) was used to observe the device's background with about (8 ± 12 Bq·m^{-3}).

3. Results

3.1. Radon exposure, attached, unattached fraction & equilibrium factor

During regular working hours, personal passive radon exposure monitors were used to gather information about radon levels. The radon exposure ranged between 223 ± 24 Bq·m^{-3} and 296 ± 47 Bq·m^{-3}, with an annual average of 261 ± 33 Bq·m^{-3}. These values were utilized to calculate the dose conversion factor and estimate the effective dose. The relative error for each measurement was determined by calculating the standard deviation from the three times the tracks were counted and then converting them into radon concentrations. Additionally, the unattached factors (as shown in Table 1) were calculated using the measured PAEC obtained from the SARAD EQF3220.

The annual average unattached factor was measured as 0.15, 0.3, and 0.2 during working hours in three different mine areas. The values of the f_{un} show the same trend, while values were slightly higher in some points. The annual average of three areas was used for dose assessment. However, the DCF and effective dose were separately calculated and estimated based on the real measurements. Previously, other studies regarding radon measurements and dosimetry were conducted for the exact location using different measurement methods and tools, and more information can be found in Shahrokhi et al., 2017 and 2021 [15,24]. For example, in a previous study, detectors were fixed at eleven locations to determine the distribution of radon concentration. The detectors were changed and evaluated over three months. In this study, radon exposure was actively and personally monitored. Passive measurement could mislead us during the dose assessment, as the radon concentrations during working hours can differ from the whole-day averages, especially when work is organized with one shift working per day. Therefore, detectors were attached to the workers' clothes before starting the job and stored in a radon-proof box after finishing the job on the next working day to estimate the exact exposure

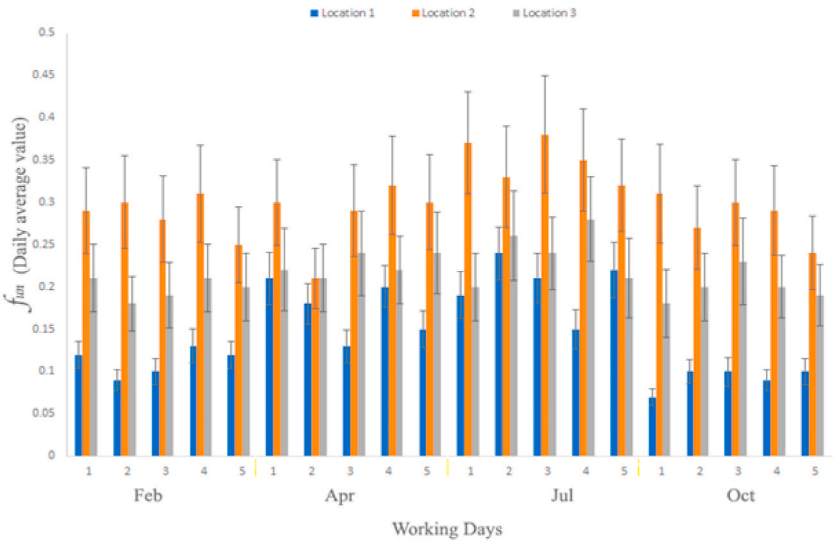

Fig. 5. A plot of 5 days unattached factor at three working locations.

Table 3
The annual average of equilibrium factor (F) at three working locations.

	Minimum	Maximum	Mean
Location 1	0.23 ± 0.12	0.79 ± 0.24	0.55 ± 0.2
Location 2	0.22 ± 0.1	0.58 ± 0.18	0.36 ± 0.1
Location 3	0.21 ± 0.1	0.57 ± 0.19	0.35 ± 0.1
∑Average	0.42 ± 0.13		

Table 4
The calculated DCF compared to the value given by ICRP ($mSv \cdot WLM^{-1}$).

	Location 1	Location 2	Location 3
f_{un}	0.15 ± 0.04	0.3 ± 0.05	0.21 ± 0.04
DCF$_m$[a]	21 ± 10	35 ± 11	26 ± 10
DCF$_n$[b]	9 ± 7	11 ± 7	10 ± 7
DCF$_{m,n}$	**16 ± 9**	**25 ± 10**	**20 ± 9**
∑Average	20 ± 9		
ICRP-137	**10**		

[a] Mouth breathing.

[b] Nose breathing.

rate. Additionally, it was found that the estimated effective doses can differ by about three times, depending on the applied equilibrium factor. Table 2 shows the influence of the equilibrium factor on the effective dose from our previous study.

As shown in Fig. 5, the unattached fraction alternately changed during the year in the exact location. Therefore, in an environment such as this study, it is recommended to frequently measure the ratio between attached and unattached fractions.

Additionally, more measurements were carried out to determine the equilibrium equivalent concentration and equilibrium factor using Pylon WLx. The average equilibrium factor was measured at about 0.35 ± 0.1, 0.36 ± 0.1, and 0.55 ± 0.2 for each location during working hours, as shown in Table 3.

3.2. Determination of dose conversion factor

To complete the dose assessment, the dose conversion factor (DCF) was calculated based on the data obtained from on-site measurements. Table 4 provides a summary of the calculated DCF compared to the DCF values provided by ICRP and WHO/USEPA. The dose conversion factors were determined by considering breathing behavior and other radiological parameters, as explained earlier. Since the breathing behavior of the miners was not observed during this experiment, the recommended values published by Porstendörfer in 1996 were used to calculate the DCF.

Fig. 6 depicts the estimated DCF values derived from considering breathing behavior, equilibrium, and the unattached factor. The

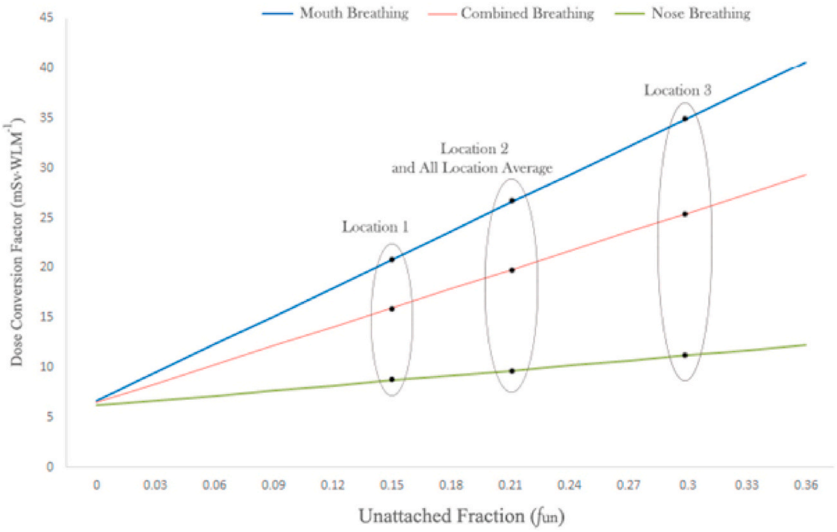

Fig. 6. DCF values based on breathing behavior and calculated the f_{un}.

Table 5
The effects of actual and recommended parameters on effective dose (E) (mSv·y^{-1}).

	Given values (F = 0.4, DCF = 10)		Experimental values (F and DCF)			
	E (ICRP)	E (USEPA/WHO)	E(ICRP)	E(USEPA/WHO)	From this study	
					F	DCF
Location 1	3.3 ± 0.4	3.2 ± 0.4	6.9 ± 0.9	7.0 ± 0.9	0.55 ± 0.2	16 ± 9
	3.3 ± 0.4	3.1 ± 0.4	6.8 ± 0.9	6.9 ± 0.9		
	3.5 ± 0.4	3.3 ± 0.4	7.1 ± 0.9	7.2 ± 0.9		
	3.6 ± 0.4	3.4 ± 0.4	7.3 ± 0.9	7.4 ± 0.9		
Location 2	3.3 ± 0.4	3.1 ± 0.4	6.9 ± 0.9	7.0 ± 0.9	0.36 ± 0.1	25 ± 10
	3.3 ± 0.4	3.1 ± 0.4	6.9 ± 0.9	7.0 ± 0.9		
	3.5 ± 0.4	3.4 ± 0.4	7.5 ± 0.9	7.6 ± 0.9		
Location 3	3.4 ± 0.4	3.2 ± 0.4	5.6 ± 0.7	5.6 ± 0.9	0.35 ± 0.1	20 ± 9
	3.6 ± 0.5	3.4 ± 0.4	5.9 ± 0.8	6.0 ± 0.7		
	3.5 ± 0.5	3.3 ± 0.5	5.8 ± 0.8	5.9 ± 0.8		
∑Average	**3.4** ± **0.4**	**3.3** ± **0.4**	**6.7** ± **0.9**	**7** ± **0.8**	**0.42** ± **0.13**	**20** ± **9**

annual average radon exposures and unattached factors were utilized to calculate the overall DCF for the entire mine, as presented in Table 4.

The DCF was suggested as 5 and 4 mSv·WLM^{-1} for workers and the general population in the ICRP-66. But in the ICRP publication [1], these values have been changed to 3 mSv per mJ·h·m^{-3} (approximately 10 mSv per WLM) for both groups (workers and public, excluded the workers in the caves where DCF suggested as 20 mSv per WLM). In most circumstances, the recommended dose is helpful for official reports; however, as shown in Table 4, there is a difference between the actual DCF and the pre-calculated value suggested by ICRP or USEPA in this study. The average dose conversion factor value (including three locations) is at least two times greater than the recommended 10 mSv·WLM^{-1}.

3.3. Effective dose estimation

The effective dose resulting from radon and its short-lived decay products was estimated using the observed data from real measurements and compared to the estimated effective dose based on the DCF recommended by ICRP and USEPA/WHO, as presented in Table 5.

The effective dose was estimated to range from 5.6 ± 0.7 to 7.5 ± 0.9 mSv y^{-1} (with a geometric mean of 6.7 ± 0.9 mSv y^{-1}) using the ICRP equation and between 5.6 ± 0.9 and 7.6 ± 0.9 mSv y^{-1} (with a mean of 7 ± 0.8 mSv y^{-1}) using the USEPA equation. When the recommended data were applied in the calculation, the estimated doses were reduced by half. Fig. 7 provides a comprehensive overview of the study, covering the methodology and the observed results in a single visualization.

It was observed that the estimated effective dose using actual field parameters is nearly double the value obtained when using the ICRP-137 or USEPA recommended data. The estimated effective doses calculated using the USEPA method are slightly higher than those obtained from the ICRP equation.

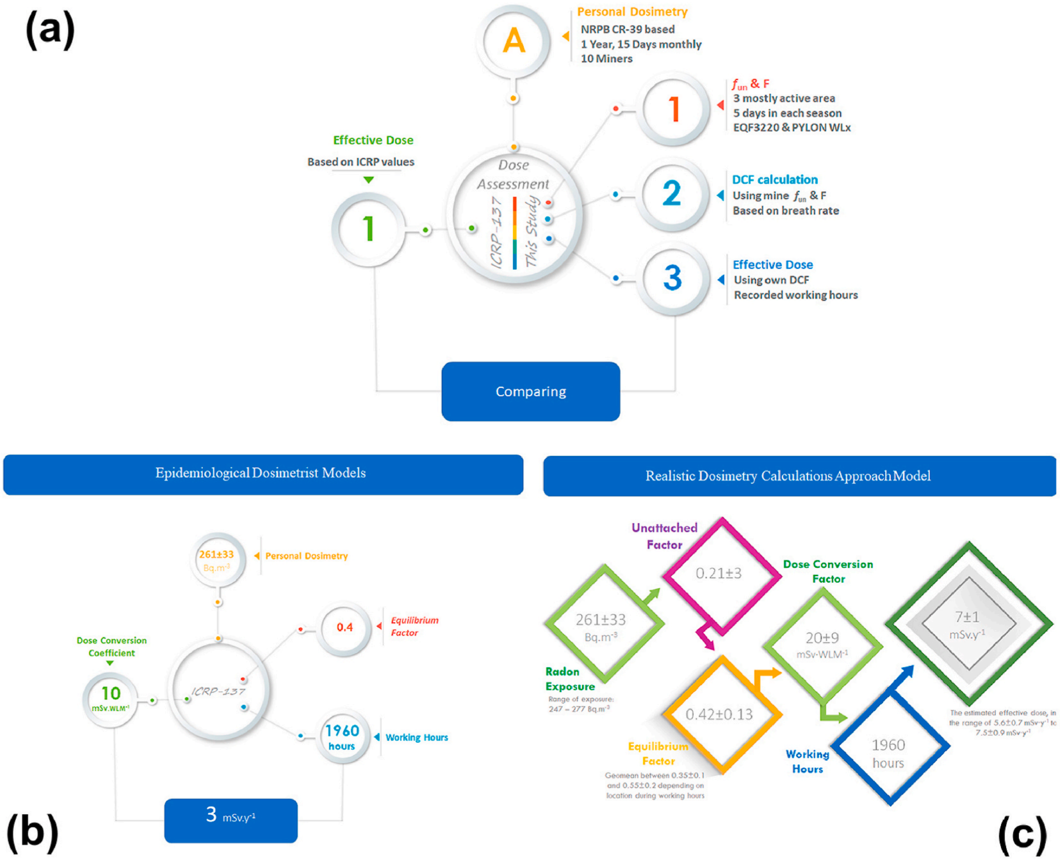

Fig. 7. Realistic calculations approach to dosimetry vs. epidemiological dosimetry model: (a) overall overview of dose assessment per each approach; (b) dose estimation based on the epidemiological model; (c) dose assessment by the realistic approach.

According to the EU-BSS, the annual average radon concentration in workplaces, including underground mines, should be kept below 300 Bq·m^{-3}. However, based on the findings of this study, miners may receive high doses even if they are exposed to radon concentrations below 300 Bq·m^{-3}. From a legislative perspective, expressing limits in terms of radon concentration (Bq·m^{-3}) is simpler as radon measurement is easier compared to dose calculations. However, from a radiation protection standpoint, relying solely on radon concentrations may not be sufficient for assessing the working environment, as demonstrated in this study.

4. Conclusions

This study aimed to assess the effects of radiological parameters on radon dose estimation in an underground mine. The levels of attached and unattached radon progeny and the radon equilibrium factor were measured. The annual average of the unattached factor ranged from 0.15 ± 0.04 to 0.3 ± 0.05, with an average of 0.21 ± 0.04. Using these values along with the measured EEC (equilibrium equivalent concentration), the average equilibrium factor was calculated, ranging from 0.35 ± 0.1 to 0.55 ± 0.2, with an average of 0.42 ± 0.13, across all representative measurement locations during working hours. Following the dose assessment, annual radon exposures were measured in the range of 247 ± 31 to 277 ± 36 Bq·m^{-3}, with an average of 261 ± 33 Bq·m^{-3}. The dose conversion factor, calculated using the parameters obtained from this study, ranged from 16 ± 9 to 25 ± 10 mSv·WLM^{-1}, with an average of 20 ± 9 mSv·WLM^{-1}. Notably, the dose conversion factor increased by 1.5 times when the unattached value changed from 0.15 to 0.3. The estimated average dose conversion factor was at least two times greater than the ICRP recommended value of 10 mSv·WLM^{-1}. Furthermore, it is recommended to conduct additional studies in different regions and underground working areas (excluding caves) with a larger sample size to gain a more comprehensive understanding of the topic.

Author contribution statement

Amin Shahrokhi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper. Tibor Kovács: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Not applicable.

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