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Preliminary Population Exposure to Indoor Radon and Thoron in Dhaka City, Bangladesh

Md. Mahamudul Hasan [1,*], Miroslaw Janik [2], Shikha Pervin [3] and Takeshi Iimoto [1]

[1] Department of Environment Systems, Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa Campus, Chiba 277-8561, Japan; iimototakeshi@g.ecc.u-tokyo.ac.jp
[2] National Institutes for Quantum Science and Technology, National Institute of Radiological Sciences, Inage Ward, Chiba 263-8555, Japan; janik.miroslaw@qst.go.jp
[3] Health Physics Division, Atomic Energy Centre Dhaka, Bangladesh Atomic Energy Commission, Dhaka 1000, Bangladesh; shikha.pervin@yahoo.com
* Correspondence: 8629731042@edu.k.u-tokyo.ac.jp

Abstract: Radon, an element of natural radiation, is considered one of the leading causes of lung cancer worldwide. In Bangladesh, radon has been clarified as a foremost source of radiation exposure. Potential natural-radiation-induced elevated cancer risks were estimated in Bangladesh previously for the population. In this survey, as a very preliminary study in the country, comparative indoor radon (^{222}Rn, Rn) and thoron (^{220}Rn, Tn) concentration/population exposure was determined for the multistoried dwellings of south-western areas of Dhaka city. RADUET was used to assess annual Rn and Tn concentrations in determining the primary inhalation dose for the population. The annual effective dose of Rn and Tn was evaluated in this study for dwellings at 0.3 mSvy^{-1}, constituting a Tn dose contribution of an average of 40% with a dwelling-based wide range of 10–96%. Thus, Tn should not be neglected for Bangladesh while estimating radiological inhalation dose from the indoor environment. Again, the equilibrium factors, F of Rn and Tn, were determined by short-term measurement at averages of 0.6 and 0.02, respectively. Furthermore, using questionnaire estimation by principal component analysis, PCA following the dwelling characteristics, human lifestyles, and estimated long-term indoor Rn and Tn concentrations, this paper discussed indoor atmospheric/Rn factors for the investigated multistoried dwellings in Dhaka city.

Keywords: Dhaka city; population exposure; radon and thoron; equilibrium factor; PCA; radon factors

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1. Introduction

In Bangladesh, elevated fatal cancer risk due to natural radiation exposure was obtained for the population [1]. The countrywide regions exhibited higher background radiation levels and soil natural radionuclide contents, i.e., ^{226}Ra and ^{232}Th [2–6]. Radon (^{222}Rn, Rn), a naturally occurring radioactive gas formed consecutively through the decaying of uranium, thorium, and radium, has been clarified as a practical environmental component to investigate the internal exposures due to natural radiation in Bangladesh [2,7]. As a radioactive gas, Rn decays, formulating progenies that stay in the air as a single cluster or attach to the existing aerosol particles by generating radioactive aerosols [8]. While humans breathe, Rn progenies come into the lungs from the air, emitting alpha rays to lung tissues through decaying and finally causing lung cancer at a particular exposure stage. Thus, Rn exposure is considered a prominent environmental cause of lung cancer after smoking [9–11]. In Bangladesh, lung cancer is found to be one of the most prevalent cancer diseases, and the prospect of Rn exposures, i.e., high Rn exhalation rates, exists in the country; however, Rn-induced lung cancer risks are unknown for the country due to insufficient nationwide systematic measurements and unknown/undetermined parameters required in Rn risk models [7]. The previous Rn studies of Bangladesh [12–18] conducted with SSNTDs, solid-state nuclear track detectors of CR-39 and LR-115, are summarized in a recent comprehensive review [7]. The Rn concentrations in different dwelling types and regions were higher than the world average, the countrywide average of other Asian countries of India, China, or Japan, and the reference levels of WHO and ICRP. As for the parameter affecting Rn concentration, previous studies assumed indoor ventilation. However, the impact of dwelling characteristics and human lifestyles on indoor ventilation is unknown and has been concentrated on in this research. In Bangladesh, systematic Rn surveys characterizing the indoor Rn spatiotemporal dynamics, factors affecting indoor Rn levels, national factors of indoor Rn distribution, suitable equilibrium factor F, or arithmetic mean on indoor Rn level are lack in determining the presumable internal dose for the population or establishing a reference level as part of controlling Rn exposures. Rn equilibrium factor RnF was measured in Bangladesh with an extensive wide range of 0.04–0.97 [12] compared to the UNSCEAR recommended value [19]. It is crucial to determine suitable values for RnF for dose estimation and reasons for the significant variation. On the contrary, thoron (^{220}Rn, Tn), an isotope of radon capable of formulating human lung exposure, can cause Bangladeshi population exposure due to the high content of its parent nuclide of thorium in the Bangladeshi soil. So far, the Tn exposure in Bangladeshi dwellings is unknown. Therefore, as part of the systematic radon study estimating indoor Rn and Tn-induced population exposure in Bangladesh, this research focused on Dhaka city's multistoried dwellings by initiating a discriminative Rn and Tn survey in the country. This very preliminary survey aims at ascertaining the country's initial discriminative doses from Rn and Tn; variability of indoor Rn, Tn, and their progenies concentrations; possible factors for the indoor atmosphere (dwellings)/ Rn concentration variation, and finally, providing recommendations for future radiological studies.

2. Materials and Methods

2.1. Site Description and Investigated Dwellings

Capital Dhaka (a city with tropical climate, average temperature of 25.3 °C) has around 18.2 million residents [20]; multistoried dwellings were chosen for increasing numbers due to population growth and urbanization. South-west regions covering around one-fourth of the area of Dhaka city were selected for measurement following the larger population [21] and availability of our categorized dwellings/rooms with potential Rn and Tn exposure. As this study is very preliminary for Tn in Bangladesh, we emphasized the rooms' building materials, measurement distance, and ventilation pattern in selecting the dwellings in the south-west area. Dwellings/rooms were selected following the possibilities of radiological exposure from building materials [22] and ventilation parameters based on our assumptions and previous Rn studies [13,14,16,18]. Dwellings were classified as *modern,* having distinctive building materials, i.e., concrete, tiles, or mosaic stone with higher ventilation choices; *apartment*, concrete with lower ventilation option; and *traditional*, an old type made of mostly similar brick-built to the Old Dhaka area having the least ventilation option. A total of 50 rooms were chosen for the measurement.

2.2. Measurement of Indoor Radon and Thoron Concentrations (Long-Term and Short-Term)

RADUET, Radosys Co. Ltd., Budapest, Hungary, was used to assess annual Rn and Tn concentrations of dwellings. The literature describes its structure and calculation procedure [23]. The detector comprises two chambers with different diffusion barriers; the varied air exchange rates allow for simultaneously measuring Rn and Tn concentration. One of the chambers is sensitive to only Rn activity, and another one is to both Rn and Tn. The CR-39 chips stay on the bottom of the chambers and register the alpha particles emitted from Rn and Tn and some of their progenies [24]. As for the etching process of the CR-39 chips (manufactured by Nagase Landauer, Ltd., Tsukuba, Japan), a 6 M NaOH solution at 60 °C for 24 h was adopted. After etching, the chips underwent natural drying at the laboratory for a day (22 °C). RADUET calibration was performed using the reference laboratory of Hirosaki University, Japan, maintaining procedures [25,26]. Image-J and microscope methods were used for track evaluation to determine Rn and Tn concentrations.

The lower detection limit of Rn and Tn concentrations were determined for RADUET as 2 Bqm^{-3} and 6 Bqm^{-3}, respectively [27].

We performed both long-term (around one year in 50 dwellings by RADUETs) and short-term (a few days to 1-month in representative dwellings) indoor Rn and Tn concentration measurements. Annual concentration estimation with RADUET represents the general room conditions covering the impact of environmental and human lifestyle on average Rn and Tn data. So far, in Bangladesh, the clarification of the temporal variation of indoor Rn and Tn concentration by continuous measurement and associated factors is unknown/lacking. As the dwelling room condition (i.e., closed up) commonly exhibits high Rn concentration; and the open window condition exhibits lower Rn level [11], we considered short-term estimation in closed room conditions to primarily understand the room's highest potential level of exposure. During the measurement, rooms were kept closed to reduce disturbance in Rn and Tn from prospective environmental factors and indoor human activities. We estimated the simultaneous indoor–outdoor atmospheric conditions (temperature, pressure, and humidity) with Thermo Recorder TR-73U (T&D CORP., Matsumoto, Japan) during the short-term measurement to identify possible atmospheric parameters affecting the temporal variation of Rn and Tn concentrations. The indoor ventilation rate (h^{-1}) was assessed by the tracer gas decay method [28,29]. The CO_2 gas concentration was measured by CO_2 Recorder RTR-576 (T&D CORP., Matsumoto, Japan). Dwelling aerosol concentration (µg/m^3) was measured by a laser particle counter DC170-PM (Dylos Corp.). The RnF and TnF were estimated in each representative dwelling category. RAD7 (Durridge Co. Inc., Bedford, MA, USA) was used for measuring simultaneous Rn and Tn concentrations. This device relies on an active method of assessing Rn (C_{Rn}) and Tn (C_{Tn}) focusing on the spectral analysis of their progenies collected through electrostatic collection. A portable silicon semiconductor working level WLx monitor (Pylon Electronics Inc., Mississauga, ON, Canada) was adopted to assess their progenies (a few days). The monitor measures Rn and Tn progenies collected by filter paper through its solid-state detector. The equivalent equilibrium concentrations of Rn ($C_{Rn,EEC}$) and Tn ($C_{Tn,EEC}$) in Bqm^{-3} from WL were evaluated by the equations [30,31] below:

$$C_{Rn,EEC} = WL \times 3700;\ C_{Tn,EEC} = WL \times 275$$

The equilibrium factors (RnF and TnF) were calculated by [32,33]

$$\text{RnF or TnF} = \frac{C_{Rn,EEC}}{C_{Rn}}; \frac{C_{Tn,EEC}}{C_{Tn}};$$

2.3. Questionnaire Estimation

A questionnaire was applied to determine influential parameters affecting indoor atmosphere/ Rn concentrations. The questionnaire content was fixed based on the author's consideration of Rn dose parameters and the assumptions of previous Rn studies in Bangladesh [12–18]. In addition, the questionnaire content of nationwide Rn surveys of Japan carried out by the Rn team of the National Institute of Radiological Sciences (NIRS) was learned in designing the content [34–36]. Questionnaire estimation was performed by the authors by recording the dwelling parameters (i.e., building materials, detector positions in rooms) during in situ measurement and interviewing the owner/representative person of each dwelling. The multivariate analysis method (principal component analysis, PCA) [37–40] was used for questionnaire estimation using IBM SPSS Software version 25.

3. Results and Discussions

3.1. Estimation of Indoor Radon and Thoron Concentrations in Dwellings of Dhaka City

Estimation results using RADUET are presented in Table 1. Rn concentration is relatively low (3 ± 2 Bqm^{-3} to 20 ± 3 Bqm^{-3}), showing an insignificant difference among our dwelling categories. While comparing with previous long-term studies for Dhaka city/Bangladesh (Table 1), our study determined a relatively lower Rn level. In this study, detectors were primarily set up on upper floors (2nd to 10th) to understand the foremost impact of building materials on indoor Rn and Tn concentration. Our study focused on the concrete building, a common type for multistoried dwellings in Dhaka city, which presented a lower Rn level. A diverse pattern of Rn concentration was found in previous studies for concrete-based dwellings in Bangladesh [7]. As observed, the Dhaka city dwellings (especially those with characteristics of modern type) exhibited elevated natural ventilation rates due to the high-rise room conditions and mechanical ventilation options. In this study, the ceiling fan was determined to be the most prominent mechanical home appliance in our investigated dwellings. Many modern dwellings presented the use of air conditioning in parallel with ceiling fans. Moreover, around 85% of dwellings presented the availability of kitchen exhaust fans in our study. These might be the probable reasons for having lower Rn levels obtained in our study. Studies [41–43] clarified similar influences of ventilation, usage of mechanical appliances, and building factors affecting indoor Rn reduction/variation.

Table 1. Long-term radon and thoron concentrations in the multistoried buildings of Dhaka city and comparison with countrywide studies using SSNTDs.

Location	Parameter	Radon Concentration (Bqm^{-3})	Thoron Concentration (Bqm^{-3})	Reference Studies
Countrywide	Range	3 to 2616	Not available	[7]
Dhaka city	Range	37 to 170	Not available	[13]
Dhaka city	Range	3–20	7–56	This study
	AM ± SD	8 ± 5	16 ± 12	
	GM	7	14	

On the other hand, obtained long-term Tn concentration (7 ± 2 Bqm^{-3} to 56 ± 8 Bqm^{-3}) was higher than Rn (Table 1). The apartment and traditional types presented larger variability of Tn concentrations (Bqm^{-3} arithmetic mean, AM = 17, standard deviation, SD = 14, geometric mean, GM = 14,) and (AM = 19, SD = 13, GM = 16,), respectively, compared to modern (AM = 12, SD = 4, GM = 11). Potentially altered Tn diffusion length due to dwelling characteristics (older type settings, building materials, exhalation rates, or wall surface status) and atmospheric or human-lifestyle-oriented ventilation rates in apartment and traditional styles might be the probable reasons for larger Tn variabilities. As the distribution of Tn gas typically depends on the distance from the room wall [44,45], we focused on the wall distances for RADUETs. The Tn concentration measured in the modern type was found to be lower (<20 Bqm^{-3}) for different wall distant positions. Instead, apartment and traditional styles expressed relatively elevated levels (i.e., 56 Bqm^{-3}) although detectors were positioned at more than 50 cm from the wall. Therefore, the chance of Tn exposures in the apartment and traditional types might be high. We assessed gamma dose rates for all the dwellings' wall surface/indoor air using an integrated gamma dosimeter (RPL dosimeter, Chiyoda Technol Corporation, Ibaraki, Japan). The obtained dose rate varied from 0.23 to 0.42 $\mu Svhr^{-1}$, representing a probable radionuclide source in the room wall (possibly parent of Tn or other).

In the case of short-term measurement, Rn concentration provided some temporal variation (9–84 Bqm^{-3}) due to the atmospheric parameters (temperature, pressure, humidity, and ventilation rate). Tn concentration was derived as an elevated level (15–428 Bqm^{-3}). The atmospheric temperature difference between the monitored room and outside was identified as a significant ($p < 0.05$) parameter of Tn variability. It is noted that our explored room was adjacent to the house's kitchen. During a one-month continuous assessment in rooms close to the kitchen, we observed a relatively extended period of the family's cooking habits, which might be one of the foremost reasons for changing indoor atmospheric conditions in the investigation room. Additionally, we applied a mechanical fan (the foremost human lifestyle for Dhaka city), which altered the indoor natural ventilation rate of 0.2 h^{-1} up to 1.2 h^{-1}, sufficiently reducing the Tn concentration at the position close to the wall. This indicates a possibility of spatial distribution or altering the Tn diffusion length due to ventilation in Dhaka city dwellings. This diffusion-mechanism-based indoor Tn distribution from the wall was also ascertained for Japanese and Chinese dwellings [46,47].

3.2. Potential Dwellings/Indoor Radon Factors for Dhaka City: Questionnaire Analysis

This study demonstrates the factors focusing on dwelling characteristics (i.e., categories, building materials, year of construction), monitored room/measurement conditions (i.e., window usage/materials, detector's distance from walls), and dweller's lifestyle (i.e., room occupancy, usage of home appliances). No prior systematic information exists in Bangladesh on how the indoor parameters depend on each other. PCA based on the correlation matrix was employed for all questionnaire parameters through, which the correlation coefficients for each of them can be observed. The coefficient is simply the correlation matrix of included variables. The significance level (p-value) associated with each correlation for parameters was investigated. Method of extraction and varimax rotation was employed in the factor analysis by two principal components.

The PCA plot (Figure 1) indicates parameter interaction by Component 1 (PC-1 covering 20% of total variance) and Component 2 (PC-2 covering 13% of total variance). Parameter positions in the PCA plot identify the groups with their elements (marked with ellipse shape), in which the variables can affect each other positively; and negatively to the opposite group in the plots. Parameters under the human lifestyle of activities in the kitchen (cooking and water usage) are correlated with water usage in the bathroom (group on the right in the plot). Following the lifestyle of food preparation for Dhaka city, kitchen activities are found in our study as mostly longer, possibly because of the curry-based cooking system. This might offer long periods of water usage (cooking and cleaning), altering the indoor atmospheric conditions. PC-1 comprises strong positive loadings for cooking time, source (Rn), and water usage. Previous Rn studies in Bangladesh clarified ventilation as one of the foremost Rn parameters [7,48] for which our study newly determined building characteristics and human lifestyle parameters. The natural ventilation level has been clarified as an indoor factor (strong positive loading by PC-2). We obtained a group in the plot (right upper side consisting of natural ventilation and building characteristics) for which the measured room's dwelling airtightness and windows number are identified as ventilation parameters. PC-2 expresses a group in the left middle of the plot where usage of air conditions and mosquito coils (indoor aerosol source for Dhaka city) is found to have strong positive loadings. Another group is in the plot's upper left, ensuring the profound impact of human activities in altering natural ventilation.

Based on the parameter's significant values ($p < 0.05$) obtained interactively with the correlation matrix analysis, dwellings (*modern*, *apartment*, and *traditional*) can be categorized in the criteria of construction age, building materials, window material, room types, home appliances, air tightness, number and occupancy for dwellers, room door/water usage, considerable outdoor source of Rn, and the measured Rn, Tn concentrations. Based on the correlation matrix, we compared variables for the three dwelling types; the coefficients were obtained at 0.48 for building year, 0.32 for air tightness, 0.61 for window usage in summer hours per day, and 0.30 for Tn concentration. This indicates relatively older settings and airtight rooms with somewhat elevated Tn for *traditional* dwelling types. Alternatively, home appliances express coefficients of (−0.50), occupant's number of (−0.54), outdoor source status of (−0.35), window materials of (−0.44), cooking material of (−0.37), room occupancy of (−0.49), door and ceiling fan usage of (−0.43) and (−0.36), and Rn concentration of (−0.32) in comparison to the dwelling types; which that indicated dwellers of the *modern* house are larger in number, staying extended period in dwellings with home appliances and door usage. Overall, the older dwellings are different ($p < 0.05$) from the new ones in terms of air tightness, building materials, ventilation, and Tn concentrations. Our findings will be effective in explaining the high Rn concentration of old dwellings in Bangladesh [14].

Indoor parameters	Mark	**Questionnaire elements**
Building specific factor	✱	Dwelling category, building year, number of floor, room type, wall/roof/floor material, window material/leakage, home appliances in investigated rooms/dwelling, cooking material, presence of kitchen ventilator
Source/potential-human exposure	▲	Radon concentration, thoron concentration, error for radon/thoron, possible outdoor source for radon, detector distances from wall/floor/roof, dwellers sleeping tendency closed to wall
Natural ventilation	●	Natural ventilation level, sufficiency of airflow in summer/winter
Building characteristics (driven ventilation)	●	Air tightness of investigation rooms/dwellings, numbers of window
Human activities related to ventilation	■	Room occupancy, occupant number, mechanical fan/air condition usage in different seasons, door/window usage, tendency to keep room closed, concern about indoor air pollution, mosquito coil usage, smoking habit, satisfaction with indoor ventilation
Human activities in kitchen	◆	Water usage in kitchen, cooking time, position of kitchen close to living room
Human activities(water usage) in bathroom	◆	Water source and usage in bathroom

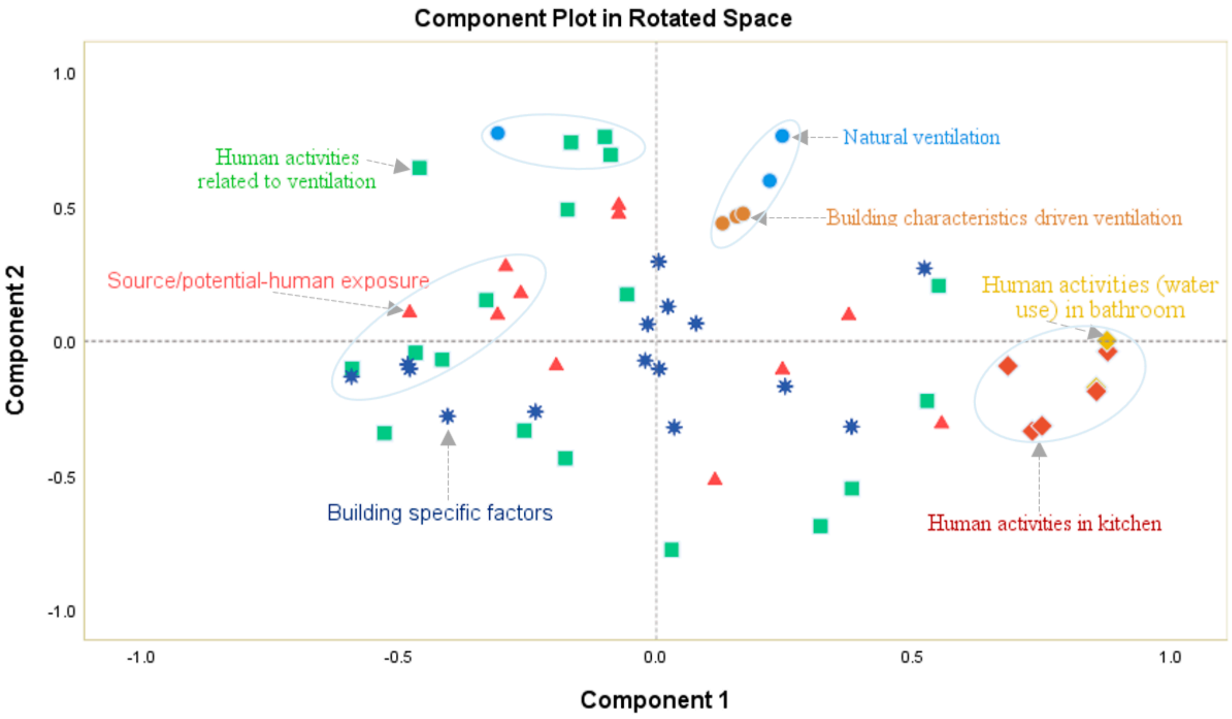

Figure 1. Distribution of dwelling factors among two principal component plots, component 1 (PC−1) and component 2 (PC−2).

As significant Rn parameters, building characteristics (dwelling category, building materials, outdoor Rn source, presence of kitchen near the living room, material and usage of window, water source), human lifestyle (cooking time, water usage), sufficiency/satisfaction on indoor ventilation by residents are determined. Distinctive building materials, i.e., mosaic stones or tiles, are used in multistoried buildings, especially in *modern* dwellings, which might be a source of Rn. Dwelling structures (steel, glass, or polymer as window or door materials) of *modern* type might affect indoor Rn increasing airtightness. Correlation analysis indicated that dwellers' dissatisfaction with indoor ventilation is also a factor in augmenting Rn; with Rn, window usage presents a negative coefficient (−0.34), along with cooking time (−0.50) and water usage (−0.34). Window usage in Dhaka city multistoried buildings might enhance air exchange with outside fresh air and thus reduce indoor Rn concentration. A study [49] clarified that the room window affects the air exchange rate, meteorological conditions, and airtightness in altering indoor Rn concentrations. Kitchen activities are associated with changing indoor atmospheric conditions [50–52]. Longer cooking may change the ventilation rate (due to the exhaust fan usage), dwelling atmospheric temperature and pressure, and water content in the building materials of Dhaka city. Thus, cooking and water usage may impact the exhalation rate and pumping effect of Rn and Tn from building materials forming radiological exposures following the environmental mechanism described by studies [53,54]. In the PCA plot, they mostly stand in opposite positions of Rn, being possible countermeasures approach for indoor Rn in Dhaka city. In the absence of proper ventilation due to aging/cracks of building materials/energy efficient strategy, studies [42,55] determined elevated accumulation of Rn gas in the upper floor apartment buildings for which bidirectional ventilation was found to be more effective than unidirectional type in reliable Rn gas reduction. Obtained primary Rn factors in this study, window materials and usage, or dwelling category might formulate indoor conditions as the diverse energy efficient conditions, which might even affect the indoor Rn variation of our investigation.

3.3. Preliminary Indoor Radon and Thoron Equilibrium Factors (RnF, TnF) in Dhaka City

RnF and TnF were determined by short-term measurements for representative modern (5th floor), apartment (2nd floor), and traditional (2nd floor) types of dwellings. Detectors were placed in the middle of the room, keeping closed room conditions. The average RnF and TnF were obtained as 0.6 and 0.02, respectively. Rn concentrations of apartment and modern types show higher levels than traditional (Table 2). RADUET data achieved through the long-term estimation presented a similar tendency of somewhat elevated levels for apartment and modern types. As shown in Table 2, the apartment type expressed an elevated average RnF of 0.8; the investigated room's position was adjacent to the kitchen, which might increase the aerosol concentrations in the measurement room enhancing the Rn progeny attachment. On the other hand, our estimation of Tn equilibrium factor TnF was found to be different in average values for the three types of dwellings: apartment (0.03) > modern (0.02) > traditional (0.01). The review paper explaining worldwide TnF [33] expressed a larger variation (0.003–0.14) based on the detector's positions of the room's building materials (i.e., wall); most of the measurements were within at least 10 to 20 cm from foremost Tn source (breathing zone). Our investigation was conducted far from the source (at least greater than 50 cm from the wall due to the difference in room size), and we missed systematically assessing important parameters investigation (ventilation rate, aerosol number concentration, or atmospheric condition information). Thus, we cannot compare our values with a specific indoor environmental condition worldwide. However, based on the influence of RnF, we primarily assume factors (indoor ventilation, possible Tn source, or aerosol number concentrations).

Table 2. Assessment of Rn and Tn equilibrium factors in multistoried buildings of Dhaka city based on very preliminary study (AM ± SD, GM).

Dwelling Types (Room Numbers)	Radon Concentration Bqm^{-3}	Radon Equilibrium Factor	Thoron Concentration Bqm^{-3}	Thoron Equilibrium Factor
Modern	14 ± 4, 14	0.4 ± 0.2, 0.4	32 ± 12, 30	0.02 ± 0.01, 0.02
Apartment	18 ± 3, 17	0.8 ± 0.2, 0.8	30 ± 17, 27	0.03 ± 0.02, 0.03
Traditional	9 ± 3, 9	0.5 ± 0.2, 0.5	31 ± 16, 27	0.01 ± 0.0004, 0.01

Dhaka was demonstrated as one of the top cities in the world for kitchen aerosol exposure, relying mostly on only natural ventilation as an exhaust system [56]. Moreover, outdoor sources (i.e., traffic, industrial activities, or transboundary pollution) lead Dhaka city to extreme aerosol pollution [57]. An aerosol study [58] conducted in apartment-type dwellings of our measurement areas indicated that a dwelling's biomass burning could pose aerosol pollution for several dwellings. Following the location of aerosol pollution in Dhaka city clarified by the studies [57,58] and considering Dhaka city is one of the most densely populated by inhabitants, we performed a second-time in situ survey on additional experiments of RnF in a western area of the capital. The hourly measurement of Rn and Tn concentrations (around one month by RAD7) and indoor Rn progeny concentration (grab sampling method) were carried out in a *modern* type (5th floor) multistoried dwelling. Atmospheric parameters and aerosol number concentrations were also assessed. The room was also kept closed to avoid human activities, and the measurement point was close to the wall to observe the room wall strength, especially for Tn gas. One of the RADUETs was previously set up in one bedroom of the building (3rd floor of the same building), which exhibits a significantly lower annual concentration level of Rn = 8 ± 2 Bqm^{-3}; Tn = below the lower detection limit. However, in our survey, indoor Rn and Tn concentrations, Bqm^{-3} were (AM = 31, SD = 15, GM = 27) and (AM = 171, SD = 87, GM = 147), respectively. Thus, our assessment expressed much higher Rn and Tn levels than the long-term estimation in the same building. Although the building materials are similar for rooms on the 3rd and 5th floor, material collection during the building construction work (i.e., bricks, cement, or sand) might be from different sources at various times, posing distinctive source strengths even in the same dwelling. Primarily the assessed atmospheric conditions (temperature, pressure, and humidity) were determined as one of the foremost factors in larger Rn time variation. Overall, the average indoor RnF was measured at 0.4 ± 0.2 with a range of 0.2 to 0.9. One of the factors affecting the variation of indoor progeny concentrations was the outside temperature measured at other common spaces in the dwelling and indoor aerosol concentration measured by particle counter DC170-PM (the correlation coefficient between aerosol number concentration and radon progeny concentration is 0.6). The indoor–outdoor temperature difference is the indicator of ventilation and is associated with the outdoor air supply [59]; thus, the temperature-driven ventilation rate of summer might influence the aerosol attachment mechanism with Rn progeny; and entry of aerosols from the outdoor or adjacent kitchen through the window/door gap, and finally affecting the RnF.

3.4. Internal Population Exposures for Dhaka City: Annual Effective Dose from Indoor Radon and Thoron

Using the long-term Rn and Tn concentrations, a population-based annual effective dose was obtained by the UNSCEAR formula [19,60]:

$$E = C \times F \times OF \times DCF$$

E = annual effective dose from Rn and Tn (mSvy^{-1}), C = average concentration of Rn or Tn (Bqm^{-3}), F = equilibrium factors of Rn or Tn, we used UNSCEAR recommended value of 0.4 for Rn and 0.02 for Tn; similar values were obtained in our short-term estimation of the equilibrium factor in Section 3.3 (second-time in situ radon F survey following aerosol and atmospheric condition measurement determined average Rn equilibrium factor as 0.4), OF = home occupancy time (7000 h), DCF = dose conversion factor, (Rn = 9 nSv $(\text{Bqm}^{-3}\text{h})^{-1}$); Tn = 40 nSv $(\text{Bqm}^{-3}\text{h})^{-1}$).

Our estimated total internal dose (0.30 mSvy^{-1}) is lower than the world average [61]. In the case of Rn, the average internal dose was estimated at 0.20 ± 0.13 mSvy^{-1} ranging from 0.01 to 0.50 mSvy^{-1}. *modern* and *apartment* types expressed around similar Rn dose levels (average 0.22 ± 0.14 mSvy^{-1}; 0.20 ± 0.10 mSvy^{-1}, respectively) exhibiting relatively higher levels than *traditional* (0.14 ± 0.12 mSvy^{-1}). *modern* and *apartment* types are based on concrete walls, having tiles or mosaic stone, whereas *traditional* is mainly made with brick or concrete without coating or painting. We assume that their building material source is also different by region. Moreover, other distinctive dwelling factors (i.e., ventilation) could impact the distribution of Rn gas indoors and the exposures from Rn progenies.

In the Tn case, the average annual effective dose was measured at 0.1 $mSvy^{-1}$ with a range of 0.03 to 0.3 $mSvy^{-1}$. Tn demonstrates an average of 40% with a 10–96% range of total inhalation dose from Rn and Tn. The estimated Tn dose level is similar to the world average; however, its contribution to total inhalation dose is much higher than the world average of 10% [61,62]. Hence, Tn could not be neglected while estimating inhalation dose from natural radiation for Bangladesh. Dwellings under the *apartment* and *traditional* types expressed more significant variations (representing Tn dose as 0.1 ± 0.08 $mSvy^{-1}$ and 0.1 ± 0.07 $mSvy^{-1}$, respectively) than *modern* (0.07 ± 0.02 $mSvy^{-1}$). In general, the main contributor of Tn dose in a room is the Tn progeny of Pb-212, having a relatively longer half-life of 10.6 h, which might be influenced by Dhaka city's diverse indoor ventilation parameters in terms of attaching to indoor aerosol particles and distribution into rooms positions.

4. Conclusions

The country's very preliminary comparative indoor atmospheric Rn and Tn concentration, equilibrium factors, and population inhalation dose were assessed in 50 multistoried buildings of south-western Dhaka city. This study's newly estimated dwelling Tn concentration for Bangladesh expressed a relatively larger time variation (15 to 428 Bqm^{-3}) with some possibilities of potential factors' (atmosphere, lifestyle, or source strength) impact. Rn or Tn equilibrium factors were found to be varied with investigated dwelling types, measurement positions, room size, and influence of human activities (aerosols). The Rn- and Tn-induced internal dose in our study of 0.3 $mSvy^{-1}$ expresses a safer level. Tn dose contribution to total inhalation dose varies for the investigated dwelling types. Using questionnaire analysis by PCA, we primarily identified human-lifestyle-oriented parameters as activities in the kitchen (i.e., cooking, water usage) and bathroom (i.e., water usage for cleaning). The newly indicated interactive ventilation parameters will be helpful in explaining assumed Rn factors (ventilation) by previous studies. Our study was conducted in the most populated area of the capital with several dwelling/room types, a future systematic study covering all regions of the capital, building spatiotemporal dynamics assessment for indoor Rn and Tn gas, factor analysis with adequate dwelling numbers, and understanding indoor progeny distribution for complex indoor aerosol dynamics following sources (cooking, traffic) is strongly recommended.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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References

1. Chakraborty, S.R.; Alam, M.K. Countrywide Radiation Dose in Different Locations, Dwellings and Free Spaces of Bangladesh. *Radiat. Prot. Dosim.* **2014**, *162*, 638–648. [CrossRef] [PubMed]
2. Chowdhury, M.I.; Chowdhury, M.R.; Alam, M.N. Study of Radon Exhalation from Soil to Ascertain the Elevated Levels of Background Radiation of Bangladesh. *Radioprotection* **2002**, *37*, 325–328. [CrossRef]
3. Hamid, B.N.; Chowdhury, M.I.; Alam, M.N.; Islam, M.N. Study of Natural Radionuclide Concentrations in an Area of Elevated Radiation Background in the Northern Districts of Bangladesh. *Radiat. Prot. Dosim.* **2002**, *98*, 227–230. [CrossRef]
4. IAEA—International Atomic Energy Agency. *Environmental Monitoring for Radiological Safety in South-East Asia, the Far East and the Pacific Regions*; IAEA-TECDOC-228; IAEA: Vienna, Austria, 1980.

5. Mollah, A.S.; Rahman, M.M.; Koddus, M.A. Measurement of High Natural Background Radiation Levels by TLD at Cox's Bazar Coastal Areas in Bangladesh. *Radiat. Prot. Dosim.* **1987**, *18*, 39–41. [CrossRef]
6. Khan, R.; Islam, H.M.T.; Islam, A.R.M.T. Mechanism of Elevated Radioactivity in Teesta River Basin from Bangladesh: Radiochemical Characterization, Provenance and Associated Hazards. *Chemosphere* **2021**, *264*, 128459. [CrossRef] [PubMed]
7. Hasan, M.M.; Janik, M.; Sakoda, A.; Iimoto, T. Status of Radon Exposure in Bangladeshi Locations and Dwellings. *Environ. Monit. Assess.* **2021**, *193*, 770. [CrossRef] [PubMed]
8. Porstendörfer, J. Properties and Behaviour of Radon and Thoron and Their Decay Products in the Air. *J. Aerosol Sci.* **1994**, *25*, 219–263. [CrossRef]
9. ATSDR. *Toxicological Profile for Radon: Agency for Toxic Substances and Disease Registry (ATSDR)*; ATSDR: Atlanta, GA, USA, 2012. Available online: https://www.atsdr.cdc.gov/toxprofiles/tp145.pdf (accessed on 25 April 2023).
10. Gaskin, J.; Coyle, D.; Whyte, J.; Krewksi, D. Global Estimate of Lung Cancer Mortality Attributable to Residential Radon. *Environ. Health Perspect.* **2018**, *126*, 057009. [CrossRef]
11. WHO. *WHO Handbook on Indoor Radon*; WHO: Geneva, Switzerland, 2009. Available online: https://apps.who.int/iris/bitstream/handle/10665/44149/9789241547673_eng.pdf (accessed on 25 April 2023).
12. Farid, S.M. Equilibrium Factor and Dosimetry of Radon by CR-39 Nuclear Track Detector. *Radiat. Prot. Dosim.* **1993**, *50*, 57–61. [CrossRef]
13. Farid, S.M. Measurement of Concentrations of Radon and Its Daughters in Indoor Atmosphere Using CR-39 Nuclear Track Detector. *Nucl. Tracks Radiat. Meas.* **1993**, *22*, 331–334. [CrossRef]
14. Hamid Khan, M.A.; Chowdhury, M.S. Radon Measurements in Some Areas in Bangladesh. *Radiat. Meas.* **2008**, *43* (Suppl. 1), S410–S413. [CrossRef]
15. Haque, A.K.F.; Islam, G.S.; Uddin, M.R.; Islam, M.A. Indoor and Underground Radon Activity in the Northern Part of Bangladesh: A Preliminary Study. *Int. J. Radiat. Appl. Instrum. Part D* **1991**, *18*, 341–344. [CrossRef]
16. Islam, G.S.; Islam, M.A.; Farid, S.M.; Rahman, A. A Study of Radon Activity inside Some Houses in Bangladesh. *Int. J. Radiat. Appl. Instrum. Part D* **1988**, *15*, 551–554. [CrossRef]
17. Khan, M.A.H.; Chowdhury, M.S. The Measurement of Radon Working Levels at a Mineral Separation Pilot Plant in Cox's Bazar, Bangladesh. *Health Phys.* **2003**, *85*, 466–470. [CrossRef]
18. Srivastava, A.; Zaman, M.R.; Dwivedi, K.K.; Ramachandran, T.V. Indoor Radon Level in the Dwellings of the Rajshahi and Chuadanga Regions of Bangladesh. *Radiat. Meas.* **2001**, *34*, 497–499. [CrossRef]
19. United Nations Scientific Committee on the Effects of Atomic Radiation. *ANNEX D: Evaluation of Occupational Exposure to Ionizing Radiation*; United Nations Scientific Committee on the Effects of Atomic Radiation: Vienna, Austria, 2022; Volume 4.
20. Swapan, M.; Zaman, A.; Ahsan, T.; Ahmed, F. Transforming Urban Dichotomies and Challenges of South Asian Megacities: Rethinking Sustainable Growth of Dhaka, Bangladesh. *Urban Sci.* **2017**, *1*, 31. [CrossRef]
21. Bangladesh Bureau of Statistics. *Population & Housing Census 2011, Zila Report: Dhaka*; Bangladesh Bureau of Statistics: Dhaka, Bangladesh, 2015. Available online: http://203.112.218.65:8008/WebTestApplication/userfiles/Image/PopCenZilz2011/Zila_Dhaka.pdf (accessed on 25 April 2023).
22. Asaduzzaman, K.; Mannan, F.; Khandaker, M.U.; Farook, M.S.; Elkezza, A.; Amin, Y.B.M.; Sharma, S.; Kassim, H.B.A. Assessment of Natural Radioactivity Levels and Potential Radiological Risks of Common Building Materials Used in Bangladeshi Dwellings. *PLoS ONE* **2015**, *10*, e0140667. [CrossRef]
23. Tokonami, S.; Takahashi, H.; Kobayashi, Y.; Zhuo, W.; Hulber, E. Up-to-Date Radon-Thoron Discriminative Detector for a Large Scale Survey. *Rev. Sci. Instrum.* **2005**, *76*, 113505. [CrossRef]
24. Janik, M.; Al-Azmi, D.; Sahoo, S.K. The Screening Indoor Radon and Preliminary Study of Indoor Thoron Concentration Levels in Kuwait. *Radiat. Prot. Dosim.* **2018**, *181*, 246–254. [CrossRef]
25. Pornnumpa, C.; Oyama, Y.; Iwaoka, K.; Hosoda, M.; Tokonami, S. Development of Radon and Thoron Exposure Systems at Hirosaki University. *Radiat. Environ. Med.* **2018**, *7*, 13.
26. Kranrod, C.; Tamakuma, Y.; Hosoda, M.; Tokonami, S. Importance of Discriminative Measurement for Radon Isotopes and Its Utilization in the Environment and Lessons Learned from Using the RADUET Monitor. *Int. J. Environ. Res. Public Health* **2020**, *17*, 4141. [CrossRef]
27. *ISO 16641:2014(E)*; Measurement of Radioactivity in the Environment—Air—Radon 220: Integrated Measurement Methods for the Determination of the Average Activity Concentration Using Passive Solid-State Nuclear Track Detectors. ISO: Geneva, Switzerland, 2014.
28. Guo, H.; Morawska, L.; He, C.; Gilbert, D. Impact of Ventilation Scenario on Air Exchange Rates and on Indoor Particle Number Concentrations in an Air-Conditioned Classroom. *Atmos. Environ.* **2008**, *42*, 757–768. [CrossRef]
29. Dovjak, M.; Virant, B.; Krainer, A.; Zavrl, M.Š.; Vaupotič, J. Determination of Optimal Ventilation Rates in Educational Environment in Terms of Radon Dosimetry. *Int. J. Hyg. Environ. Health* **2021**, *234*, 113742. [CrossRef] [PubMed]
30. ICRP. *ICRP Occupational Intakes of Radionuclides: Part 3*; ICRP Publication 137; ICRP: Ottawa, ON, Canada, 2017; Volume 46. Available online: https://www.icrp.org/publication.asp?id=ICRP%20Publication%20137 (accessed on 25 April 2023).
31. Kávási, N.; Somlai, J.; Vigh, T.; Tokonami, S.; Ishikawa, T.; Sorimachi, A.; Kovács, T. Difficulties in the Dose Estimate of Workers Originated from Radon and Radon Progeny in a Manganese Mine. *Radiat. Meas.* **2009**, *44*, 300–305. [CrossRef]

32. Chen, J.; Harley, N.H. A Review of Indoor and Outdoor Radon Equilibrium Factors—Part I: 222Rn. *Health Phys.* **2018**, *115*, 490–499. [CrossRef] [PubMed]
33. Chen, J.; Harley, N.H. A Review of Indoor and Outdoor Radon Equilibrium Factors—Part II: 220Rn. *Health Phys.* **2018**, *115*, 500–506. [CrossRef]
34. Suzuki, G.; Yamaguchi, I.; Ogata, H.; Sugiyama, H.; Yonehara, H.; Kasagi, F.; Fujiwara, S.; Tatsukawa, Y.; Mori, I.; Kimura, S. A Nation-Wide Survey on Indoor Radon from 2007 to 2010 in Japan. *J. Radiat. Res.* **2010**, *51*, 683–689. [CrossRef] [PubMed]
35. Iimoto, T.; Tokonami, S.; Yonehara, H.; Furuta, S.; Shimo, M. Researches and Activities on Radon/Thoron and NORM for Past 30 Years in Japan. *Radiat. Environ. Med.* **2021**, *10*, 55–66.
36. Janik, M.; Bossew, P.; Hasan, M. Indoor Radon Research in the Asia-Pacific Region. *Atmosphere* **2023**, *14*, 948. [CrossRef]
37. George, D.; Mallery, P. *IBM SPSS Statistics 25 Step by Step: A Simple Guide and Reference*, 15th ed.; Routledge: Abingdon-on-Thames, UK, 2018.
38. Lever, J.; Krzywinski, M.; Altman, N. Points of Significance: Principal Component Analysis. *Nat. Methods* **2017**, *14*, 641–642. [CrossRef]
39. Shahrokhi, A.; Adelikhah, M.; Chalupnik, S.; Kovács, T. Multivariate Statistical Approach on Distribution of Natural and Anthropogenic Radionuclides and Associated Radiation Indices along the North-Western Coastline of Aegean Sea, Greece. *Mar. Pollut. Bull.* **2021**, *163*, 112009. [CrossRef] [PubMed]
40. Bellucci, A.; Tondelli, A.; Fangel, J.U.; Torp, A.M.; Xu, X.; Willats, W.G.T.; Flavell, A.; Cattivelli, L.; Rasmussen, S.K. Genome-Wide Association Mapping in Winter Barley for Grain Yield and Culm Cell Wall Polymer Content Using the High-Throughput CoMPP Technique. *PLoS ONE* **2017**, *12*, e0173313. [CrossRef] [PubMed]
41. Gulan, L.; Stajic, J.M.; Spasic, D.; Forkapic, S. Radon Levels and Indoor Air Quality after Application of Thermal Retrofit Measures—A Case Study. *Air Qual. Atmos. Health* **2023**, *16*, 363–373. [CrossRef]
42. Choi, J.; Hong, H.; Lee, J.; Kim, S.; Kim, G.; Park, B.; Cho, E.; Lee, C. Comparison of Indoor Radon Reduction Effects Based on Apartment Housing Ventilation Methods. *Atmosphere* **2022**, *13*, 204. [CrossRef]
43. Iimoto, T. Time Variation of the Radon Equilibrium Factor in a Reinforced Concrete Dwelling. *Radiat. Prot. Dosim.* **2000**, *92*, 319–321. [CrossRef]
44. Sanada, T. Measurement of Indoor Thoron Gas Concentrations Using a Radon-Thoron Discriminative Passive Type Monitor: Nationwide Survey in Japan. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1299. [CrossRef]
45. Urosevic, V.; Nikezic, D.; Vulovic, S. A Theoretical Approach to Indoor Radon and Thoron Distribution. *J. Environ. Radioact.* **2008**, *99*, 1829–1833. [CrossRef] [PubMed]
46. Zhuo, W.; Chen, B.; Wei, M. Estimation of Indoor 220Rn Progeny Concentrations with 220Rn Measurements. *Radiat. Prot. Dosim.* **2010**, *141*, 408–411. [CrossRef]
47. McLaughlin, J. An Overview of Thoron and Its Progeny in the Indoor Environment. *Radiat. Prot. Dosim.* **2010**, *141*, 316–321. [CrossRef]
48. Pervin, S.; Yeasmin, S.; Khandaker, M.U.; Begum, A. Radon Concentrations in Indoor and Outdoor Environments of Atomic Energy Centre Dhaka, Bangladesh, and Concomitant Health Hazards. *Front. Nucl. Eng.* **2022**, *1*, 901818. [CrossRef]
49. Cucu, M.; Dupleac, D. The Impact of Ventilation Rate on Radon Concentration Inside High-Rise Apartment Buildings. *Radiat. Prot. Dosim.* **2022**, *198*, 290–298. [CrossRef]
50. Zhao, Y.; Tao, P.; Zhang, B.; Huan, C. Contribution of Chinese Hot Pot and Barbecue Restaurants on Indoor Environmental Parameters. *Aerosol Air Qual. Res.* **2020**, *20*, 2925–2940. [CrossRef]
51. Deng, N.; Fan, M.; Hao, R.; Zhang, A.; Li, Y. Field Measurements and Analysis on Temperature, Relative Humidity, Airflow Rate and Oil Fume Emission Concentration in a Typical Campus Canteen Kitchen in Tianjin, China. *Appl. Sci.* **2022**, *12*, 11755. [CrossRef]
52. Ravindra, K.; Agarwal, N.; Kaur-Sidhu, M.; Mor, S. Appraisal of Thermal Comfort in Rural Household Kitchens of Punjab, India and Adaptation Strategies for Better Health. *Environ. Int.* **2019**, *124*, 431–440. [CrossRef]
53. Janik, M.; Omori, Y.; Yonehara, H. Influence of Humidity on Radon and Thoron Exhalation Rates from Building Materials. *Appl. Radiat. Isot.* **2015**, *95*, 102–107. [CrossRef] [PubMed]
54. Sun, Q.; Tokonami, S.; Yamada, Y.; Akiba, S. Main Meteorological Parameters to Influence Indoor Radon Level. *Radioisotopes* **2002**, *51*, 120–126. [CrossRef]
55. Yarmoshenko, I.V.; Onishchenko, A.D.; Malinovsky, G.P.; Vasilyev, A.V.; Nazarov, E.I.; Zhukovsky, M.V. Radon Concentration in Conventional and New Energy Efficient Multi-Storey Apartment Houses: Results of Survey in Four Russian Cities. *Sci. Rep.* **2020**, *10*, 18136. [CrossRef]
56. Kumar, P.; Hama, S.; Abbass, R.A.; Nogueira, T.; Brand, V.S.; Wu, H.W.; Abulude, F.O.; Adelodun, A.A.; Anand, P.; Andrade, M.d.F.; et al. In-Kitchen Aerosol Exposure in Twelve Cities across the Globe. *Environ. Int.* **2022**, *162*, 107155. [CrossRef]
57. Moniruzzaman, M.; Shaikh, M.A.A.; Saha, B.; Shahrukh, S.; Jawaa, Z.T.; Khan, M.F. Seasonal Changes and Respiratory Deposition Flux of PM2.5 and PM10 Bound Metals in Dhaka, Bangladesh. *Chemosphere* **2022**, *309*, 136794. [CrossRef] [PubMed]
58. Weaver, A.M.; Gurley, E.S.; Crabtree-Ide, C.; Salje, H.; Yoo, E.H.; Mu, L.; Akter, N.; Ram, P.K. Air Pollution Dispersion from Biomass Stoves to Neighboring Homes in Mirpur, Dhaka, Bangladesh. *BMC Public Health* **2019**, *19*, 425. [CrossRef] [PubMed]
59. Sorimachi, A.; Tokonami, S.; Omori, Y.; Janik, M.; Iwaoka, K.; Ishikawa, T.; Sun, Q. Characteristics of Indoor Radon and Thoron Concentrations in Cave Dwellings in Gansu Province, China. *Radiat. Prot. Dosim.* **2019**, *184*, 457–462. [CrossRef] [PubMed]

60. Chen, J. A Review of Radon Exposure in Non-Uranium Mines—Estimation of Potential Radon Exposure in Canadian Mines. *Health Phys.* **2023**, *124*, 244–256. [CrossRef] [PubMed]
61. UNSCEAR. *Sources, Effects and Risks of Ionizing Radiation*; United Nations Scientific Committee on the Effects of Atomic Radiation: Vienna, Austria, 2008; Volume 1.
62. Hosoda, M.; Kudo, H.; Iwaoka, K.; Yamada, R.; Suzuki, T.; Tamakuma, Y.; Tokonami, S. Characteristic of Thoron (220Rn) in Environment. *Appl. Radiat. Isot.* **2017**, *120*, 7–10. [CrossRef] [PubMed]