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Assessment of Radon Gas Concentration and Radiation Doses in Dwellings in Koudougou, Burkina Faso

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Abstract Radon is a significant source of natural ionizing radiation exposure in homes and represents a risk factor for lung cancer. This study aims to characterize radon concentrations in homes in the city of Koudougou and to assess the dosimetric consequences associated with occupant exposure. The PCE-RD 75 active detector was used for volumetric radon concentration measurements in 80 studied dwellings. The mean cumulative concentrations obtained ranged from 12 to 642 Bq·m^{-3}, with an average of 54.4 ± 76.5 Bq·m^{-3}. The majority of homes have concentrations below the reference level of 100 Bq·m^{-3} recommended by the World Health Organization. However, seven homes exhibited concentrations above this value; notably, one home recorded a concentration of 642 Bq·m^{-3}, exceeding the WHO's upper reference level of 300 Bq·m^{-3}. From the measured concentrations, the annual absorbed doses were estimated to be between 0.265 and 14.172 mSv·year^{-1}, with an average of 1.201 mSv·year^{-1}. The estimated annual effective doses at the lung level range from 0.636 to 34.013 mSv·yr^{-1}, with an average of 2.882 mSv·yr^{-1}, while those estimated at the blood level range from 0.013 to 0.669 mSv·yr^{-1}, with an average of 0.057 mSv·yr^{-1}. The highest values are observed in dwellings with the highest radon concentrations, notably dwellings 60, 67, and 78. The risk assessment indicates an average lifetime probability of developing lung cancer of 1.03%, with values ranging from 0.23% to 12.16%.

Keywords: *radon, dwellings, concentration, effective dose, lung, cancer*

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1. Introduction

Radon (^{222}Rn) is a naturally occurring, colorless, and odorless radioactive gas resulting from the radioactive decay of uranium-238, which is naturally present in rocks and soil. Radon can migrate through soil pores and fissures and enter buildings, particularly homes. Foundations, cracks in slabs and walls, piping, and interfaces between the ground and built structures serve as entry points for radon into buildings. Certain construction materials and water used inside homes can also be sources of radon in buildings. Once inside, radon can accumulate when air exchange is insufficient [1,2].

Radon exposure is currently a significant public health issue in residential buildings and schools where occupants may be exposed. Radon is classified as a lung carcinogen, and prolonged exposure is primarily associated with the development of lung cancer. Radon decays into short-lived radioactive progeny: ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po. These progenies can attach to airborne aerosols and be inhaled. The deposition of radon progeny in the respiratory tract can cause cellular damage and DNA alterations through the irradiation of lung tissue by alpha particles emitted during decay [1,2].

Epidemiological studies on radon indicate that the risk of lung cancer increases with residential radon exposure. An analysis of fifty-five (55) studies on radon in homes highlights a significant association between exposure and lung cancer, with a pooled odds ratio of 1.38 for high exposure levels. The results of these studies highlight the importance of residential radon exposure as a lung cancer risk factor for occupants [1]. A study published in 2024 also concludes that there is strong evidence of an association between indoor radon exposure and lung cancer [3].

Time spent in the home accounts for a significant portion of daily life, making the health risk associated with radon exposure a matter of importance. Radon concentrations in homes vary widely across locations and over time. This variability depends on radium and uranium concentrations in the soil and rock, the permeability of the geological substrate, foundation characteristics, building materials, the building's airtightness, weather conditions, and the air exchange rate [4].

Radon concentration in homes is a key indicator for characterizing population exposure. The World Health Organization (WHO) recommends a reference level of 100 Bq·m^{-3} for the annual average radon concentration in homes. Concentrations in homes should not exceed 300

$Bq \cdot m^{-3}$. It should be noted that the reference level does not mark a boundary between "safety" and "danger," but rather represents a level above which measures to reduce exposure should be considered [5,6].

Recent studies show that concentrations exceeding these reference levels can be found in certain regions of the world. For example, a study conducted in China across 2,875 homes reported an arithmetic mean concentration of 65 $Bq \cdot m^{-3}$, with 13.6% of homes showing concentrations exceeding 100 $Bq \cdot m^{-3}$ and 0.6% exceeding 300 $Bq \cdot m^{-3}$ [7].

In sub-Saharan Africa, very few studies have been conducted on residential radon compared to certain regions of Europe, North America, and Asia. However, existing research reveals significant variability in radon concentrations across different regions, linked to diverse geological settings, building materials, architectural practices, and climatic conditions. A study on residential radon exposure near gold mining tailings indicates concerning levels of exposure in certain mining communities in South Africa, Ghana, and Cameroon [8].

The issue of radon is relevant in African countries, as radon monitoring programs in residential settings remain limited. Beyond simply measuring radon concentration, exposure assessment should account for building occupancy times, the equilibrium factor between radon and its progeny, dose conversion coefficients, and the physiological characteristics of the occupants. Factoring in these parameters will enable a more accurate estimate of the dose received by respiratory tissues and a better assessment of lung cancer risk.

In Burkina Faso, the diversity of geological settings, construction materials, and housing architectural styles makes characterizing radon levels in homes important. Existing data are limited and derived from isolated studies conducted in specific cities. There is a need to develop more extensive measurement campaigns to better characterize the spatial and temporal distribution of ^{222}Rn in homes, identify areas and dwellings with high concentrations, and estimate potential dosimetric and health consequences for exposed populations. Against this backdrop, studying radon gas concentrations in homes in the city of Koudougou is of significant scientific and public health interest. Measuring indoor concentrations will make it possible to characterize occupant exposure levels and estimate the associated doses and potential lung cancer risk.

2. Materials and Methods

2.1. Description of the Study Area

The study was conducted in the city of Koudougou, located 100 km west of the capital, Ouagadougou. It covered eighty households within the city of Koudougou. Figure 1 shows the locations of the houses included in the study.

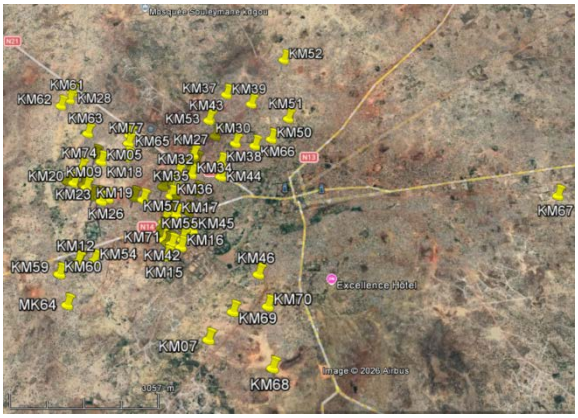


Figure 1. Location of measurement sites in the city of Koudougou

2.2. Radon Measurement Equipment Used

The PCE-RD 75 radon detector was used to measure radon gas volume concentration in residential settings during this study. It is a high-precision instrument for monitoring and alerting on radon concentration, designed to detect alpha radiation resulting from radon decay.

The PCE-RD 75 is an active radon measurement device that operates on a real-time measurement principle. It functions by drawing ambient air either via a small pump or through natural diffusion into a detection chamber where alpha particles emitted by radon are detected; this allows for the calculation of radon concentration and provides near-instantaneous results.



Figure 2. PCE-RD 75 radon detector

2.3. Dose Assessment and Lifetime Risk Probability

Radon is a major source of human exposure. It is present in homes. Calculating the annual absorbed dose and the annual effective dose makes it possible to assess the radiological risks associated with radon exposure. Lifetime risk probability allows for the assessment of the lifetime cancer risk associated with radon inhalation.

2.3.1. Annual absorbed dose

The formula used to calculate the annual absorbed dose is as follows:

$$D_{abs}\left(mGv.y^{-1}\right) = C_{Rn} * F * O * T * D_C \quad (1)$$

Where $C_{Rn}(Bq.m^{-3})$ is the indoor radon concentration, T is the annual exposure time (8760 h/year), F is the equilibrium factor (0.4), O is the occupancy factor (70%), and D_C is the dose conversion factor. The dose conversion factor is 9 nSv/(Bq·h·m⁻³) [9,10,11,12,13,14,15,16].

2.3.2. Annual Effective Dose in Lung

The annual effective dose due to radon in lung (ED_l) is determined using the annual absorbed dose (D_{abs}), the radiation weighting factor (W_R), which is 20 for alpha particles and the tissue weighting factor (W_T), which is 0.12 for the lung. The formula for calculating the effective lung dose is as follows [9,12,13,15]:

$$ED_l\left(mSv\right) = D_{abs}.W_R.W_T \quad (2)$$

2.3.3. Effective Dose in the Blood

During the respiratory process, a small amount of inhaled radon (indoors or outdoors) dissolves in the blood and can result in a certain radiation dose; the annual effective dose corresponding to this fraction can be estimated using the following equation:

$$ED_{bl}\left(mGv.y^{-1}\right) = C_{Rn} * t * O * DCF_{bl} \quad (3)$$

Where ED_{bl} represents the annual effective dose due to radon dissolved in the blood via inhalation, in mSv/y; C_{Rn} is the radon concentration in the air, in Bq/m³; t is the total duration of a year in hours (8,760 h); O is the occupancy factor (0.7 for indoors and 0.3 for outdoors); and DCF_{bl} is the dose conversion factor for radon dissolved in the blood via inhalation (the value of 0.17×10^{-6} mSv·(Bq·h·m⁻³)⁻¹, recommended in the UNSCEAR report 2000, was used to estimate ED_{bl}) [11,17,18].

2.3.4. Lifetime Risk Probability

Based on the assumption of a linear, no-threshold dose-effect relationship and on nominal risk coefficients adjusted for detriment, the lifetime risk associated with radon inhalation can be estimated using the following equation:

$$LRP = ED.LE.NRC \quad (4)$$

where LRP represents the lifetime risk probability; LE, the average lifetime expectancy (65 years in Burkina Faso); ED, the annual effective dose due to the inhalation of radon and its progeny, in mSv/year; and NRC, the nominal risk coefficient, the value of which for cancer is 5.5×10^{-2} /Sv [11,19].

3. Results and Discussion

3.1. Radon Concentration in Houses in the City of Koudougou

Figure 3 presents the cumulative average radon (²²²Rn) concentrations measured in the eighty dwellings studied in the city of Koudougou.

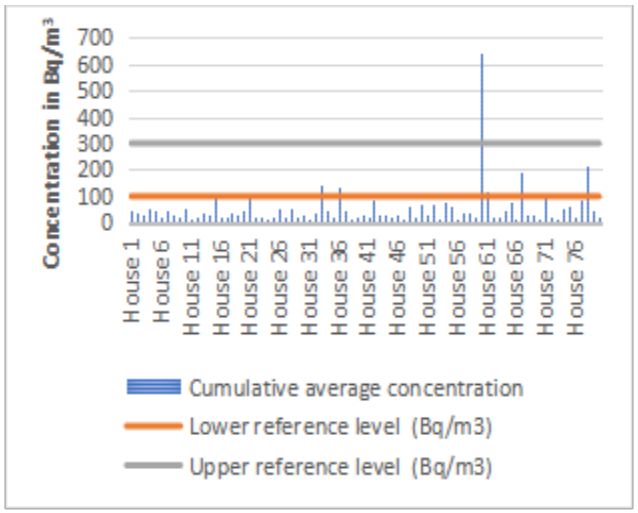


Figure 3. Variation in the cumulative average radon gas concentration in eighty houses in the city of Koudougou

Figure 3 shows that the majority of the dwellings studied in the city of Koudougou exhibit cumulative average radon concentrations below the 100 Bq·m⁻³ reference level recommended by the World Health Organization (WHO). However, some dwellings show concentrations exceeding this reference value. These include dwellings 21, 33, 36, 60, 61, 67, and 78, where the cumulative average radon concentrations are 113, 145, 138, 642, 117, 194, and 215 Bq·m⁻³, respectively.

Among these dwellings, house 60 stands out due to a particularly high cumulative average concentration, reaching 642 Bq·m⁻³. This value is well above the 300 Bq·m⁻³ reference level adopted for the analysis, which is based on WHO recommendations. This high concentration indicates potentially significant radon exposure for the occupants, which could increase health risks associated with the prolonged inhalation of radon and its short-lived radioactive progeny specifically the risk of lung cancer.

These results highlight the need to pay special attention to the dwellings with the highest concentrations, particularly house 60. It is recommended that corrective measures be implemented to reduce radon exposure, such as improving ventilation, increasing indoor air exchange, sealing radon entry points from the ground, and where necessary installing specific radon reduction systems. A follow-up measurement campaign after intervention would allow for the assessment of the effectiveness of the corrective measures adopted.

Table 1 presents the minimum, maximum, and mean values and the standard deviation for radon concentrations measured after one hour of exposure, cumulative concentration peaks, and mean cumulative concentrations recorded in the eighty homes studied in the city of Koudougou.

Radon concentrations measured after one hour in the studied homes range from 5 to 310 Bq·m⁻³, with a mean value of 47.5 Bq·m⁻³. This mean value remains below the 100 Bq·m⁻³ reference level recommended by the World Health Organization (WHO). However, some homes exhibit concentrations exceeding this reference level, indicating relatively higher exposure situations that require special attention.

Table 1. Mean, minimum, and maximum values for concentrations after one hour of measurement, cumulative concentration peaks, and cumulative concentrations

	Concentration after one hour	Peak cumulative concentration	Cumulative concentration
Mean	47.5	252.4	54.4
Minimum	5	39	12
Maximum	310	7510	642
Standard Deviation	46.8	831.2	76.5

Peaks in cumulative radon concentration range from 39 to 7,510 Bq·m⁻³, with a mean value of 252.4 Bq·m⁻³. The maximum value observed highlights significant variability in concentrations between homes. Although the mean peak value exceeds 100 Bq·m⁻³, this indicator must be interpreted differently from average exposure concentration, as peaks represent maximum instantaneous or cumulative values and do not directly characterize the occupants' chronic exposure. Nevertheless, they can reveal episodes of high radon accumulation in certain homes and warrant further investigation into ventilation conditions, building characteristics, and potential radon entry pathways.

Mean cumulative radon concentrations recorded in the studied homes range from 12 to 642 Bq·m⁻³, with a mean of 54.4 Bq·m⁻³ and a standard deviation of 76.5 Bq·m⁻³. The overall mean value thus remains below the 100 Bq·m⁻³ reference level. However, the wide range between minimum and maximum values, along with the relatively high standard deviation, reflects significant heterogeneity in radon concentrations from one home to another. This variability could be linked to differences in the architectural and structural characteristics of the buildings, the materials used, ventilation conditions, the airtightness of structures in contact with the ground, and local geological and soil characteristics.

Overall, the results show that, despite an average concentration below the reference level of 100 Bq·m⁻³, some homes exhibit significantly higher radon levels. These homes therefore warrant special attention, particularly through longer-term measurements to better characterize the occupants' actual exposure and, where necessary, the implementation of measures to reduce indoor radon concentrations.

3.2. Estimation of Absorbed and Effective Doses

Table 2 presents the minimum, maximum, and mean values and the standard deviation of the measured radon concentrations, the estimated annual absorbed and effective doses to the lungs and blood, based on the radon concentrations measured in the eighty dwellings studied in the city of Koudougou.

Table 2 presents the minimum, maximum, and mean values, as well as the standard deviation, for the measured radon concentrations and the estimated annual absorbed and effective doses to the lungs and blood, based on radon concentrations measured in the eighty homes studied in the city of Koudougou.

The estimated annual absorbed doses in the various homes studied in Koudougou range from 0.265 to 14.172 mSv·y⁻¹, with a mean value of 1.201 mSv·y⁻¹. This mean value is slightly higher than the 1.1 mSv·y⁻¹ value reported by UNSCEAR (2000) [20] for certain components of natural exposure. This result suggests a significant contribution of radon exposure to the dose received by the occupants of the studied homes. However, the comparison with the 1.1 mSv·y⁻¹ value must be interpreted with caution, as the dose attributable to radon constitutes a specific component of ionizing radiation exposure and should not be directly equated with total natural exposure.

Table 2. Mean, minimum, and maximum values of concentrations, absorbed doses, and annual effective doses

	Radon Concentration (Bq/m³)	Absorbed dose (mSv / year)	Annual effective dose to the lungs (mSv / year)	Annual effective dose to the blood (mSv / year)
Mean	54.4	1.201	2.882	0.057
Minimum	12	0.265	0.636	0.013
Maximum	642	14.172	34.013	0.669
Standard Deviation	76.5	1.689	4.054	0.08

The estimated annual effective doses to the lungs range from 0.636 to 34.013 mSv·y⁻¹, with a mean value of 2.882 mSv·y⁻¹. The mean value obtained is below the 3–10 mSv·y⁻¹ range cited in certain historical ICRP 23 [21] recommendations as the range of intervention levels for radon exposure. However, the maximum value of 34.013 mSv·y⁻¹ far exceeds this range. This high value indicates potentially significant exposure to radon and its short-lived radioactive progeny in the home in question. Such exposure, when prolonged, may contribute to an increased risk of lung cancer among the occupants. However, one should not immediately conclude that cancer will develop based solely on the estimated dose; risk assessment requires taking into account factors such as the duration of exposure, the individual characteristics of the occupants, and, where applicable, smoking habits.

The estimated annual effective doses to the blood range from 0.013 to 0.669 mSv·y⁻¹, with a mean value of 0.057 mSv·y⁻¹. These values are significantly lower than those estimated for the lungs, as exposure to radon and its radioactive progeny primarily results in the irradiation of respiratory tissues. The low estimated effective dose to the blood indicates that the contribution of systemic radon exposure to the doses received by the blood remains relatively limited under the conditions considered.

Overall, the results highlight significant variability in estimated doses across the dwellings, consistent with the variability in measured radon concentrations. Dwellings exhibiting the highest concentrations and doses should receive special attention and, where necessary, be subject to corrective measures aimed at reducing indoor air radon concentrations specifically by improving ventilation and limiting pathways for radon infiltration from the soil.

Figure 4 shows the variations in annual absorbed doses and annual effective doses to the lungs estimated for the studied houses in the city of Koudougou that had mean radon concentrations exceeding 100 Bq·m⁻³.

The estimated annual absorbed doses in houses 21 and 61 are 2.50 and 2.58 mSv·y⁻¹, respectively. These values are below the 3 mSv·y⁻¹ threshold adopted for the

comparative approach in this study, despite radon concentrations exceeding 100 Bq·m⁻³ in both houses. In contrast, the estimated absorbed doses in houses 33, 36, 67, and 78 exceed 3 mSv·y⁻¹ but remain below 10 mSv·y⁻¹. House 60 stands out due to a particularly high absorbed dose of 14.17 mSv·y⁻¹, a value exceeding 10 mSv·y⁻¹. This result indicates a particularly high level of dosimetric exposure in this house, justifying further investigation and, where appropriate, corrective measures to reduce radon concentrations.

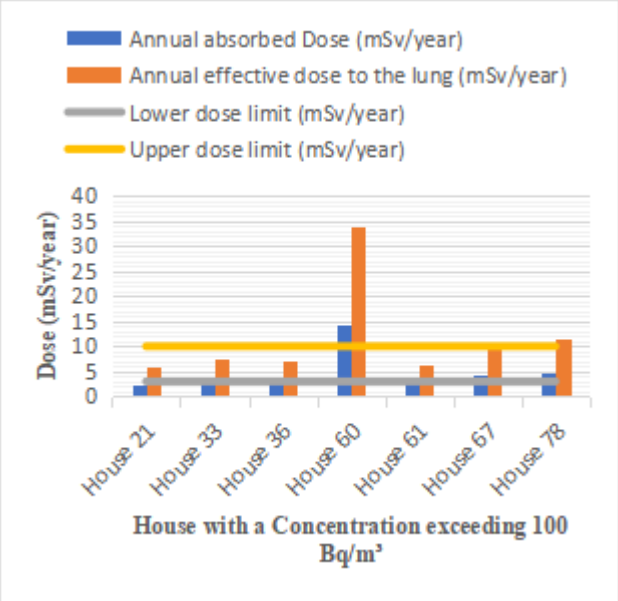


Figure 4. Variation of absorbed and effective doses in houses with concentrations exceeding 100 Bq/m³

The estimated annual effective lung doses in houses 21, 33, 36, 60, 61, 67, and 78 all exceed 3 mSv·y⁻¹. The highest values are observed in houses 60, 67, and 78, with effective lung doses of 34.01, 10.28, and 11.39 mSv·y⁻¹, respectively. These values exceed the upper threshold of 10 mSv·y⁻¹ used in the study's comparative approach.

The high effective lung dose estimated for house 60, in particular, indicates potentially significant exposure of lung tissue to radon and its short-lived radioactive progeny. Similarly, the levels estimated in homes 67 and 78 indicate significant exposure. Chronic exposure to high radon concentrations is associated with an increased risk of lung cancer. However, the effective dose estimate alone cannot predict the development of cancer in an individual; risk assessment must also take into account the duration of exposure and other individual factors, particularly smoking status.

These results thus highlight significant variability in dosimetric exposure among the homes studied. Particular attention should be paid to homes 60, 67, and 78, which exhibit the highest lung effective doses. Radon reduction measures such as improving indoor air exchange, sealing radon entry points, and, if necessary, installing an appropriate mitigation system could help reduce occupant exposure.

3.3. Probability of Lung Cancer Risk

Table 3 presents the minimum, maximum, and mean values of the lifetime probability of developing lung cancer, calculated based on effective doses.

The lifetime probability of developing lung cancer ranges from 0.23% to 12.16%, with a mean value of 1.03%. This significant variability reflects the heterogeneity of estimated risk across the studied homes, likely linked to differences in radon concentrations and, consequently, occupant exposure levels. The mean value of 1.03% corresponds to an estimated risk of approximately one case per 97 exposed individuals, based on the calculation model used in this study.

Table 3. Mean, minimum, and maximum values of the lifetime probability of lung cancer risk

	Lifetime lung cancer risk probability (LCRP) (%)
Mean	1.03
Minimum	0.227
Maximum	12.16
Standard Deviation	1.449

Overall, these results indicate that radon exposure in the homes studied in the city of Koudougou could pose a significant health risk to occupants in the event of chronic exposure. Homes showing the highest risk probabilities warrant special attention, particularly through confirmatory measurements taken over an extended period and, where necessary, the implementation of measures to reduce radon exposure.

3.4. Comparison with Other Studies

Table 4 presents the mean indoor radon concentrations obtained in selected studies conducted in Burkina Faso, Ghana, and Cameroon.

Table 4. Mean indoor radon concentrations obtained in other studies

Location	Country	Average concentration (Bq·m⁻³)	References
Koudougou (This study)	Burkina Faso	54.4	-
Ouagadougou	Burkina Faso	26.90 ± 2.58	[12]
Sissene	Burkina Faso	70.17 ± 17.94	[22]
Kaya	Burkina Faso	28.47 ± 22.22	[13]
Grand Accra	Ghana	50.8 ± 3.4	[23]
Cape Coast – Mud house	Ghana	186 ± 13.3	[24]
Cape Coast – Block house	Ghana	221 ± 61,4	[24]
Ngombas	Cameroun	33 ± 4	[25]
Akongo	Cameroun	39±11	[25]

The average radon concentration found in homes in Koudougou is higher than that reported for Ouagadougou (26.90 ± 2.58 Bq·m⁻³) [12] and that found in homes in Kaya (28.47 Bq·m⁻³) [13]. The average radon concentration obtained in this study remains lower than that measured in Sissene (70.17 ± 17.94 Bq·m⁻³) [22]. These differences reflect the spatial heterogeneity of indoor radon concentrations in Burkina Faso.

At the African level, the average concentration obtained in Koudougou is very close to those reported in certain regions of Ghana, notably Greater Accra, where an average of 50.8 ± 3.4 Bq·m⁻³ was measured [23]. However, it is higher than the average concentrations observed in some dwellings in Cameroon, particularly in the Central and Southern regions (33 ± 4 Bq·m⁻³) and in Akono (39 ± 11 Bq·m⁻³) [25]. Conversely, radon concentrations measured in homes in Cape Coast [24], Ghana, are significantly higher, with average of 186 Bq·m⁻³ for mud house and 221 Bq·m⁻³ for block house.

Overall, the average concentration of 54.4 Bq·m⁻³ obtained in Koudougou falls within the range of concentrations reported in several African studies. However, it appears higher than some values measured in Burkina Faso and Cameroon, while remaining lower than the levels observed in certain areas of Ghana. This variability could be linked to differences in the geological and soil characteristics of the sites, the uranium and radium content of the soil, building materials, the architectural features of the homes, air exchange rates, and climatic conditions. It also highlights the importance of continuing long-term measurement campaigns to better characterize the spatial and temporal distribution of radon in homes in Burkina Faso.

4. Conclusion

The objective of this study was to characterize radon gas concentrations in homes in the city of Koudougou and to assess potential dosimetric consequences. Results from the eighty homes studied show significant variability in radon gas concentrations, ranging from 12 to 642 Bq·m⁻³, with a mean of 54.4 Bq·m⁻³ and a standard deviation of 76.5 Bq·m⁻³. This wide dispersion reflects the heterogeneity of radon levels in the studied homes and could be linked to geological and soil characteristics, construction materials, building design, structural airtightness, and ventilation conditions. Overall, the mean concentration found in the homes is below the 100 Bq·m⁻³ reference level recommended by the WHO. However, seven homes exhibit concentrations above this level, with a maximum value reaching 642 Bq·m⁻³ surpassing the 300 Bq·m⁻³ threshold, which indicates a situation of particularly high exposure. Annual absorbed doses range from 0.265 to 14.172 mSv·y⁻¹, with a mean of 1.201 mSv·y⁻¹, further confirming this variability.

Estimated annual effective doses to the lungs range from 0.636 to 34.013 mSv·y⁻¹ (mean: 2.882 mSv·y⁻¹), while those estimated for the blood range from 0.013 to 0.669 mSv·y⁻¹ (mean: 0.057 mSv·y⁻¹). The highest lung doses were observed in three homes, with a maximum value of 34.01 mSv·y⁻¹, indicating high exposure for the occupants of these dwellings. The radiological risk assessment also reveals significant variation among households. The estimated lifetime probability of developing lung cancer ranges from 0.23% to 12.16%, with a mean of 1.03%. The results indicate that certain radon exposure scenarios can pose a significant health risk in cases of chronic exposure.

In conclusion, despite a relatively moderate overall average concentration, there are households with higher concentrations and doses, which may justify the implementation of residential radon monitoring in Koudougou.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of ChatGPT to assist with grammar checking, language refinement. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

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