Scientific Research Publishing

Open Journal of Applied Sciences, 2023, 13, 1066-1078
https://www.scirp.org/journal/ojapps
ISSN Online: 2165-3925
ISSN Print: 2165-3917

Assessment of Radon Concentrations inside Residential Buildings and Estimation of the Dose in the City of Kaya, Burkina Faso

Wend-Yam Appolinaire Elola[1], Telado Luc Bambara[1,2*], Ali Doumounia[1,2], Nièssan Kohio[1,2], Soumaila Ouédraogo[1,2], François Zougmore[1]

[1]Laboratoire de matériaux et Environnement, Université Joseph Ki-Zerbo, Burkina Faso
[2]Institut des Sciences et de Technologie, Ecole Normale Supérieure, Burkina Faso
Email: *telado.luc.bambara@gmail.com

How to cite this paper: Elola, W.-Y.A., Bambara, T.L., Doumounia, A., Kohio, N., Ouédraogo, S. and Zougmore, F. (2023) Assessment of Radon Concentrations inside Residential Buildings and Estimation of the Dose in the City of Kaya, Burkina Faso. *Open Journal of Applied Sciences*, **13**, 1066-1078.
https://doi.org/10.4236/ojapps.2023.137085

Received: June 18, 2023
Accepted: July 23, 2023
Published: July 26, 2023

Abstract

Colorless, incessant radon gas is notably the second most important cause of lung cancer after smoking in smokers and the first cause in non-smokers. Having little effect in the atmosphere, radon gas accumulates in confined spaces. Therefore, the determination of radon concentrations inside residential buildings is very important to improve the health of the inhabitants. The objective of this research is to measure the concentration of radon in indoor air in residential areas of the city of Kaya and to assess the absorbed dose, the effective dose and the relative risk of lung cancer. In this study, the CORENTIUM AIR THINGS digital radon detector is used to determine the radon concentration in twenty-one houses in Kaya. The CORENTIUM AIR THINGS digital radon detector has been placed in each residential building for a minimum period of one week and the concentration values are read every 24 hours. This research revealed that the average concentration of radon was 28.47 Bq/m^3 in the residential areas of Kaya. The radon concentration in a house has been found to exceed 100 Bq/m^3, which is the level authorized by the World Health Organization (WHO). In the long term, the absorbed dose varies from 0.118 mSv to 4.975 mSv and the effective dose is between 0.229 mSv and 12.002 mSv. In the short term, the absorbed dose varies between 0.095 mSv to 5.001 mSv and the effective dose is between 0.283 mSv to 11.935 mSv. The mean lung cancer relative risk (CPRR) from indoor exposure was 1.026. There is a need to raise awareness among the population of the city of Kaya on this issue and to take measures to reduce radon in homes when the concentrations are above the limit recommended by the WHO.

Keywords

Radon, Concentration, Dose, Relative Risk, Lung Cancer

1. Introduction

As part of the rare gases, radon is a colorless, odorless, incessant radioactive gas resulting from the decay of radium 226Ra itself from the decay chain of uranium 238U. In buildings, radon is considered the most important indoor air pollutant with harmful effects on the health of occupants. The main sources of radon inside homes are soil, building materials (sand, rocks, cement and bricks), water sources, natural energy sources (gas and coal) which may contain traces of uranium 238U [1].

Indeed, the quantity of radon present inside a building depends mainly on the presence of radium in the rocks and the porosity of the ground where it is built. However, porous, radon-poor soil can result in a higher concentration than low-porous, radon-rich soil. In addition, sand, cement, gravel and wild pebbles which are the main construction materials come from the earth's crust. These materials may have natural radioactivity that radiates inside homes. The concentration of radon in the indoor air of homes also depends on the condition, type and ventilation of the house. Radon can seep into homes through cracks, doors, windows and the foundation. Yet people spend more time inside houses than outside, so the inhalation of this gas is very enormous [1].

Being a radioactive gas, radon is considered by health authorities to be a pulmonary carcinogenic gas and the first factor of exposure to radioactivity in humans [2]. The concentration of radon in the outdoor air is generally very low unlike; inside houses by confinement effect, radon can accumulate to reach often very high concentrations, which represents a health risk [3].

In other words, the decay of radon 222Rn into a radioactive element by alpha particle emission can damage lung tissue. Indeed, when radon is absorbed through the respiratory tract, it can interact with biological tissues in the lungs resulting in DNA damage, which is considered an important step in the carcinogenic process [4].

Hence the study of the evaluation of the concentration of radon gas in places of residence and the estimation of the dose in the city of Kaya.

The evaluation of the radon concentration consists of determining the radon content of the indoor air of dwellings. Dose estimation consists of calculating the amount of radon absorbed in the city of Kaya.

It appears that radon is the second leading cause of lung cancer after tobacco and most cases of radon-induced lung cancer occur in smokers [5]. According to the World Health Organization (WHO in 2005), radon is the cause of 6% to 15% of all cases of lung cancer worldwide. In the United States, studies have shown that radon in homes causes 21,100 lung cancer deaths per year. It is the second leading cause of death from lung cancer [4] [6]. In Europe, radon is responsible for 9% of lung cancer deaths [5] [7].

Given that the population is still unaware of the risks associated with the cause of radon in the indoor air of habitats, and being interested in health problems, knowing the quality of indoor air is our objective in order to contribute to the improvement of the quality of life of the occupants within the buildings.

This article aims to contribute to the evaluation of the concentration of radon in buildings and its impact on the health of the inhabitants. Therefore, we will first determine the concentration of radon in residential areas in the city of Kaya before evaluating the annual effective doses of radon by inhalation due to the residence time in the buildings.

2. Materials and Methods

2.1. Materials

2.1.1. Presentation of the Study Area

The commune of Kaya, capital of the Center-North region is located 100 km from Ouagadougou, the political capital of Burkina Faso. It is located between 13˚5' North Latitude and 1˚05' West Longitude, and covers an area of 922 Km^2. The urban commune of Kaya has seven (7) sectors. Each sector of the commune of Kaya is made up of several districts. For the realization of radon gas concentration measurements in residential areas in the town of Kaya, three (3) districts were chosen per sector. One (01) house was chosen per districts, giving a total of twenty-one (21) houses studied.

Figure 1 represents a map of the houses identified for our study.

2.1.2. Measuring Instruments

AIRTHINGS CORENTIUM Home is the radon monitor suitable for family homes, public buildings and workplaces. A simple and fast instrument that can be used by everyone. Operating on batteries, AIRTHINGS CORENTIUM Home can easily be moved through the building, thus allowing to obtain a complete overview of the distribution of radon in the dwelling.

The AIRTHINGS CORENTIUM Home radon monitor samples indoor air through a passive diffusion chamber and uses alpha spectrometry to accurately

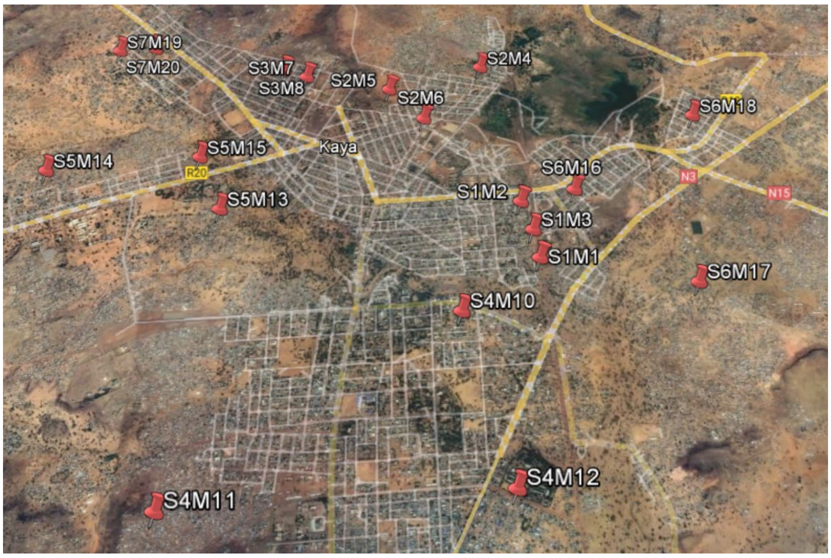

Figure 1. Location of residential study sites in Kaya. S = sector, M = house.

calculate radon concentration. The detection is done using silicon photodiodes both to count and to measure the energy of the alpha particles resulting from the chain of decomposition of the radon gas. The instrument is not sensitive to variations in temperature and humidity, to aerosols and to electromagnetic fields. It is guaranteed for one year and requires no maintenance or calibration for a lifespan of 10 years.

It is one of the three (3) best detectors for its very high precision and also in relation to its price. It is a very interesting device to know the state of indoor pollution. CORENTIUM AIR THINGS radon sensors are designed for indoor use only. The CORENTIUM AIR THINGS detector is easy to handle and move.

The CORENTIUM AIR THINGS digital radon detector is our choice for measuring radon concentration in residential buildings in the city of Kaya.

The CORENTIUM AIR THINGS Digital Radon Detector gives two values on each reading. These values are also the short-term average and the long-term average.

Figure 2 below shows the image of the radon measuring device, CORENTIUM AIR THINGS detector.

2.1.3. Radon Detection in Residential Buildings

For the concentration of radon gas measurements, the CORENTIUM AIR THINGS digital radon detector was placed inside each selected residential building for a minimum period of one week. To start the measurements, the device is reset by pressing the RESET function located on the back of the detector to erase the data from the device once inside the chosen house before starting a new measurement.

All results are given in a specific numerical value of Becquerels per cubic meter (Bq/m^3). Concentration values are read and copied onto a radon concentration data collection sheet every 24 hours for a week. The values recorded are the short-term average and the long-term average.

Figure 2. Two faces of the AIR THINGS CORENTIUM detector.

The CORENTIUM AIR THINGS Digital Radon Detector gives two values on each reading. These values are also the short-term average and the long-term average.

2.2. Dose Estimation

For a representative estimate of radon levels in residential areas, measurements were taken in occupied rooms in buildings. The absorbed dose quantifies this energy per unit mass of the organs and tissues affected. The absorbed dose in gray (Gy) is the energy in joule (J) compared to the mass in kilogram (kg) therefore (J/kg) with 1 gray (Gy) = 1 joule (J) per kilogram (kg). The regulations quantify exposure to ionizing radiation by an average dose over the whole body: the effective dose, expressed in sieverts (Sv). The effective dose balances the absorbed dose according to the radiotoxicity of the different types of radiation and the radiosensitivity of the organs and tissues. The lung is one of the most radiosensitive organs in the human body. The effective dose is an indicator of overall health detriment. The concentration of potential alpha energy of a mixture of progeny in the air is expressed in J/m^3. Beyond the relationship between the radon concentration and that of potential alpha energy, 1 Bq/m^3 = 5.56×10^{-6} mJ/m^3. The Balance factor F depends on the level of ventilation: F = 0.4 in natural ventilation and $F = 0.2$ in forced ventilation. The annual absorbed dose due to indoor exposure to radon was estimated using the radon concentration (C_{Rn}), balance factor (F), occupancy factor (O), number of hours per year (T) and the dose conversion factor (D_2) [4] [8].

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

$$D_1(\text{mSv}) = C_{\text{Rn}} * F * O * T * D_2 \quad (4)$$

with: C_{Rn} the concentration in Bq/m^3; F taken at 0.4; O estimated that people spend 80% of their time indoors; $T = 24$ hours × 365 days = 8760 h, and D_2 converts the radon concentration into a dose, 9 nSv/(Bq·m^{-3}·h^{-1}) [1] [4] [8] [9] [10] [11] [12] [13].

The dose received by the occupants is the equivalent dose on the type of radiation produced by radon as well as on the damage to organs and tissues. The effective dose equivalent was calculated using the alpha particle weighting factors for lung tissue based on ICRP, 2007.

The equivalent effective dose is estimated using the following equation:

$$E\left(\text{mSv} \cdot \text{an}^{-1}\right) = D * W * W_T \quad (5)$$

with: D represents the annual exposure dose (mSv), W a weighting factor for the alpha particle taking a value of 20 and W_T a weighting factor for the lung tissue with the value of [1] [4] [8] [9] [10] [14].

The impact of indoor radon exposure on the health of residents has been quantified by the relative risk of lung cancer (RRLC) [4] [14] [15] given by the following equation:

$$\text{RRLC} = \exp\left(0.00087352 C_{\text{Rn}}\right) \quad (6)$$

3. Results and Discussions

3.1. Radon Concentration in Some Residential Areas of Kaya

This study was conducted only in residential areas in the city of Kaya. A data collection sheet has been prepared for each habitat containing questions on the geographical information of the place of residence, the date of the start and end of the measurements, the average values of the radon concentrations in the short term and in the long term measured every 24 hours. **Table 1** gives the average, maximum, minimum and standard deviation of long-term concentration of radon in the studies houses Kaya.

The average long-term radon concentration in residential areas varies between 2.89 and 197.11 Bq/m^3. The maximum concentrations in house were between 4 and 248 Bq/m^3, and the minimum concentrations varies between 0 and 153 Bq/m^3. The long-term average concentration in all the houses was below 100 Bq/m^3, except for house 5 in sector 2. It is necessary to increase the ventilation in house 5.

Table 2 presents the average short-term and long-term radon concentrations in residential areas in Kaya town.

Table 1. Long-term radon concentration in residential areas.

Situation of houses		Long-term Radon concentration in Bq/m^3			
		Average	Maximum	Minimum	Standard deviation
Sector 1	House 1	16.67	18	13	1.70
	House 2	10.67	12	10	0.69
	House 3	5.44	7	2	2.31
Sector 2	House 4	10.44	16	7	3.09
	House 5	197.11	248	153	32.42
	House 6	37.67	48	34	4.86
Sector 3	House 7	33.44	44	22	8.34
	House 8	7.67	9	6	0.98
	House 9	2.89	4	0	1.40
Sector 4	House 10	10.33	17	4	3.16
	House 11	17.00	20	15	1.27
	House 12	4.67	6	4	1.07
Sector 5	House 13	10.44	17	9	2.79
	House 14	22.67	27	10	5.98
	House 15	7.78	10	7	1.15
Sector 6	House 16	71.33	94	63	13.98
	House 17	32.11	42	26	6.44
	House 18	32.44	38	28	4.04
Sector 7	House 19	25.78	32	24	2.75
	House 20	20.44	26	18	3.08
	House 21	20.89	31	19	4.35

Table 2. Average radon concentration in residential areas of Kaya.

	Concentration of radon in Bq/m^3	
	Short-term	Long-term
Average	25.68	28.47
Standard deviation	21.27	22.22
Minimum	3.78	2.89
Maximum	198.22	197.11

The short-term concentration varies between 3.78 and 198.22 Bq/m^3 with an average of 25.68 Bq/m^3 and the long-term concentration was between 2.89 and 197.11 Bq/m^3 with an average of 28.47 Bq/m^3. Both the short-term and long-term maximum values are above the WHO limit of 100 Bq/m^3 [16].

The results of the concentration measurements highlight the extremely variable nature of the average long-term and short-term radon concentration in the different residential buildings chosen in Kaya. According to **Figure 3**, the highest average concentrations of radon in houses at Kaya were around 200 Bq/m^3 in the short term and in the long term. The histograms of the measurements show extreme values of radon concentration according to the houses.

In conclusion, the average radon concentration in house 5 was the highest in the short and long term and was around 200 Bq/m^3, followed by house 16 which has an average concentration of 71.33 Bq/m^3 in the long term and of 64.67 Bq/m^3 in the short term. The high average concentration in House 5 may be related to building materials. It is necessary that this house can be ventilated to prevent the occupants from being exposed and developing the health effects.

Figure 4 shows us the variation in the long-term and short-term average concentration in house 5 of Kaya during the seven days of measurement. The concentration during the seven days of measurement was greater than 150 Bq/m^3; which is above the WHO lower limit, but below the upper limit of 300 Bq/m^3 [17]. The inhabitants of this house can be exposed to radon and develop the health effects.

3.2. Absorbed Dose and Effective Dose

The dose is the quantity of ionizing radiation interacting with the molecules of the human body by depositing an energy capable of damaging them. The absorbed dose quantifies this energy per unit mass of the organs and tissues affected and the effective dose quantifies the exposure to ionizing radiation by an average dose over the whole body.

Most of the dose received by the lung does not come from the radon gas itself but from the short-lived descendants with which it is in partial equilibrium. However, the conversion of radon exposure into a dose is the subject of debate within the radiation protection community. The respective views of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)

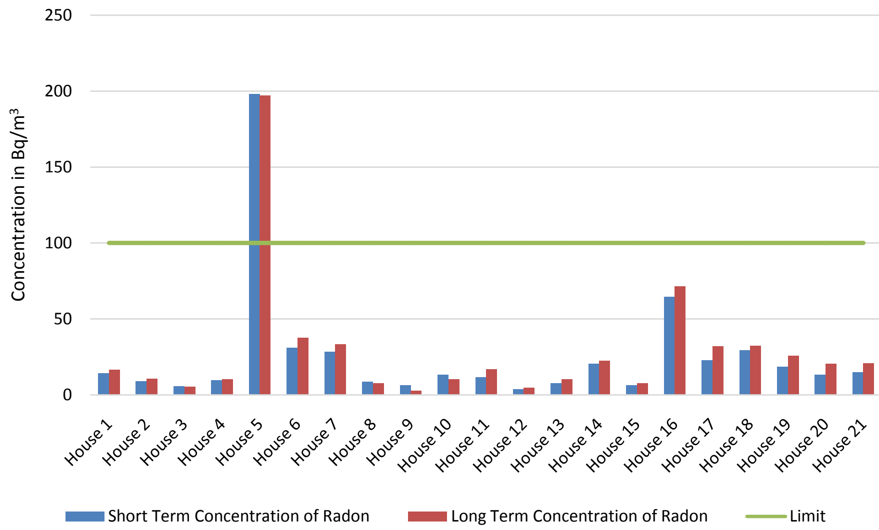

Figure 3. Radon concentration in houses.

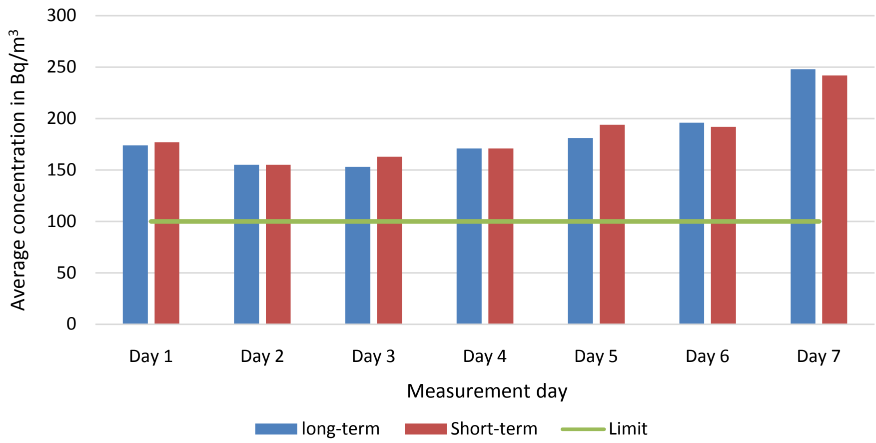

Figure 4. Variation of radon concentration in the house 5 per day.

and the International Commission on Radiological Protection (ICRP) have been analyzed and the limit is 1 to 10 mSv respectively [17] [18].

Table 3 gives the different absorbed and effective doses at short and long term.

The **Table 3** show a significant variation of radon dose in different places of residence.

In the long term, the absorbed dose varied from 0.118 mSv to 4.975 mSv and the effective dose from 0.229 mSv to 12.002 mSv. In the short term, the absorbed dose varies between 0.095 mSv and 5.001 mSv and the effective dose is between 0.283 mSv and 11.935 mSv.

The maximum value absorbed and effective doses were determined in house 5. The absorbed dose in the lungs in the short term and long term in house 5 was 5.001 mSv and 4.973 mSv respectively, that in house 16 in the short term and long term was 1.631 mSv and 1.800 mSv respectively. The absorbed dose in the other houses was less than 1 mSv.

Table 3. Absorbed dose and effective dose at short and long term.

Situation of Houses		Absorbed Dose of radon at short term	Absorbed Dose of radon at long-term	Short term effective Dose	Long-term effective Dose
Sector 1	House 1	0.362	0.420	0.868	1.009
	House 2	0.224	0.269	0.538	0.646
	House 3	0.149	0.137	0.357	0.330
Sector 2	House 4	0.247	0.264	0.592	0.632
	House 5	5.001	4.973	12.002	11.935
	House 6	0.785	0.950	1.884	2.281
Sector 3	House 7	0.715	0.844	1.716	2.025
	House 8	0.216	0.193	0.518	0.464
	House 9	0.163	0.073	0.390	0.175
Sector 4	House 10	0.334	0.261	0.801	0.626
	House 11	0.294	0.429	0.706	1.029
	House 12	0.095	0.118	0.229	0.283
Sector 5	House 13	0.199	0.264	0.478	0.632
	House 14	0.524	0.572	1.258	1.372
	House 15	0.163	0.196	0.390	0.471
Sector 6	House 16	1.631	1.800	3.916	4.319
	House 17	0.575	0.810	1.379	1.944
	House 18	0.743	0.819	1.783	1.964
Sector 7	House 19	0.471	0.650	1.130	1.561
	House 20	0.339	0.516	0.814	1.238
	House 21	0.378	0.527	0.908	1.265

The short-term effective lung doses in houses 5, 6, 7, 14, 16, 17, 18 and 19 were above the "normal" background level of 1.1 mSv per year proposed by UNSCEAR-2000 [8]. In the long term, the effective doses in the lungs for houses 5, 6, 7, 14, 16, 17, 18, 19, 20 and 21 were above the "normal" background level of 1.1 mSv per year proposed by UNSCEAR-2000. Which shows that the level of exposure in houses 5, 6, 7, 14, 16, 17, 18, 19, 20 and 21 was higher than the level proposed by UNSCEAR-2000, hence the need to take measures of radiation protection to lower concentrations.

The short-term and long-term effective lung dose in house 16 was above the lower limit of 3 mSv per year recommended by ICRP-23. In house 5, the short-term and long-term effective dose to the lungs was 12.002 mSv and 11.935 mSv respectively and above the upper limit of 10 mSv per year recommended by ICRP-23 [19]. The occupants of house 5 are susceptible to radon-related illnesses. Houses 5 and 16 are still to be checked in terms of ventilation. House 5 is a potential danger for the occupants.

3.3. Relative Risk of Lung Cancer

Chronic exposure to radon explains the appearance of cancer in occupants spending a lot of time in places where the concentration is very high. The most well-known effect associated with radon exposure is a risk of contracting lung cancer. It is noted that radon is the second cause of lung cancer after smoking. Smokers exposed to radon have a 10 to 15 times risk of developing lung cancer compared to a non-smoker. A dosimetric model represents the deposition of short-lived radon descendants, in the form of nanometric alpha (α) particles free fraction or attached to atmospheric dust in the respiratory tract according to their thermodynamic and aerodynamic properties and the resulting irradiation. If radon is inhaled, it decays into solid radioactive descendants that settle in the lungs. These solid radioactive daughters which constitute the energy of this radiation can fracture the double helix of the Deoxyribonucleide Acid (DNA).

The variations in relative risk of lung cancer in the different houses are approximately from 1.003 to 1.188 with an average of 1.026. The relative risk of lung cancer in house 5 is 1.188 higher than in the other houses. The mean relative risk of lung cancer is low; which does not constitute a carcinogenic risk for the inhabitants of the houses studied.

Figure 5 shows the relative risk of lung cancer according to each of the 21 houses studied.

The Lung Cancer Relative Risk Histogram clearly shows the different levels of risk in all the homes studied. On the histogram, we observe that the relative risk of lung cancer in house 5 was close to 1.2 and was the highest among the houses studied. The second highest value of the relative risk of lung cancer was obtained in house 16. The relative risk of lung cancer for the others houses were around one (01).

In conclusion, the variations in relative risk of lung cancer in the different houses are approximately from 1.003 to 1.188 with an average of 1.026 which is negligible.

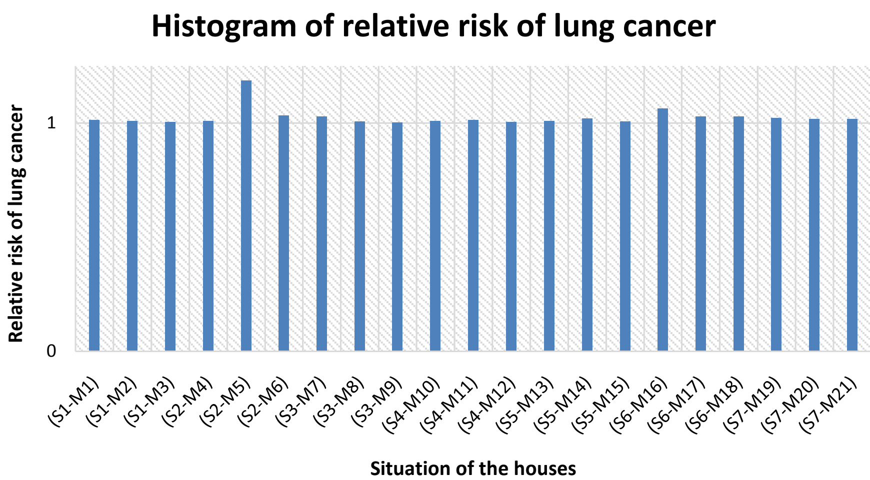

Figure 5. Relative risk of lung cancer in different houses in Kaya.

Table 4. Comparison of mean concentration with other study.

Location	Average Concentration Bq/m^3	Reference
This Study (Kaya)	28.47	
Ouagadougou	26.90 ± 2.58	Bambara *et al.*, 2021 [4]
Banlieue du Ghana	57 ± 39	Kitson-Mills *et al.*, 2019 [20]
Soudan (Kordufan)	109.43	Hajo *et al.*, 2020 [21]
Soudan (Wad Elmahi)	41	Hajo *et al.*, 2020 [21]
Marocco	80	Choukri *et al.*, 2019 [22]
Beijing (China)	(42.0 ± 13.7)	Hao Wang *et al.*, 2022 [23]

3.4. Comparisons of Concentrations with Other Studies Carried Out

Table 4 presents the average radon concentration in Kaya residential areas and that of other studies carried out in Burkina, Ghana, Sudan, Morocco and China.

The average radon concentration in Kaya is slightly higher than that obtained in homes in the city of Ouagadougou [4]. The average radon concentrations in similar studies carried out in Ghana, Sudan, Morocco and China show that the average concentration of homes in Kaya is low compared to that obtained in these countries.

4. Conclusion

The results of this study indicated that the long-term average concentration was less than 100 Bq/m^3 in most of the houses studied in the city, except for house 5 where the average concentration was 197.11 Bq/m^3. So, these results allow us to confirm that the health risk linked to the presence of radon and its radioactive descendants is low in most of the dwellings chosen and studied in the city of Kaya. On the other hand, house 5, which has concentrations greater than 100 Bq/m^3, may present a potential danger for the occupants. But ventilation, aeration, improving the sealing of walls and floors contribute favourably to reducing the concentration of radon inside dwelling houses. Health authorities should consider indoor radon to be an important environmental risk factor in Kaya city because the effective dose of radon in some of the residential buildings is often above the recommended action level limit of 3 to 10 mSv per year as reported by ICRP-1993.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Khalid, N., Majid, A.A. and Yahaya, R. (2015) Radiological Risk of Building Materials Using Homemade Airtight Radon Chamber. *AIP Conference Proceedings*, **1584**, 207-210. https://doi.org/10.1063/1.4866132

[2] Baubron, J.C., Jeandel, C. and Fourniguet, G. (2002) Evaluation du potentiel de contamination par le radon des habitations du département de la Moselle (57). Etude réalisée dans le cadre des actions de Service public du BRGM 02-POL-505. Rapport BRGM/RP-51943-FR.

[3] Autorité de sûreté nucléaire (ASN) (2020) Plan National D'action 2020-2024 Pour la Gestion du Risque Lié au Radon. https://www.asn.fr/l-asn-informe/dossiers-pedagogiques/le-radon-et-les-professionnels/plans-nationaux-d-action/plan-national-d-action-2020-2024-pour-la-gestion-du-risque-lie-au-radon-national-action-plan-2020-2024-for-management-of-the-radon-risk

[4] Luc, B.T., Karim, K., Moumouni, D., Cedric, B., Cisse, O.I. and Zougmore, F. (2021) Assessment of Indoor Radon Concentration in Residential Buildings at Ouagadougou and Estimation of the Annual Effective Dose. *Radiation Science and Technology*, **7**, 41-46. https://doi.org/10.11648/j.rst.20210702.14

[5] López-Pérez, M., Hernández, F., Díaz, J.P. and Salazar-Carballo, P.A. (2022) Determination of the Indoor Radon Concentration in Schools of Tenerife (Canary Islands): A Comparative Study. *Air Quality, Atmosphere & Health*, **15**, 825-835. https://doi.org/10.1007/s11869-022-01186-z

[6] Al Zabadi, H., Musmar, S., Issa, S., Dwaikat, N. and Saffarini, G. (2012) Évaluation de l'exposition au radon dans les réserves d'eau potable: Une étude descriptive en Palestine. *BMC Research Notes*, **5**, Article No. 29. https://doi.org/10.1186/1756-0500-5-29

[7] Darby, S., Hill, D., Auvinen, A., Barros-Dios, J.M., Baysson, H., Bochicchio, F., Deo, H., Falk, R., Forastiere, F., Hakama, M., Heid, I., Kreienbrock, L., Kreuzer, M., Lagarde, F., Mäkeläinen, I., Muirhead, C., Oberaigner, W., Pershagen, G., Ruano-Ravina, A., Ruosteenoja, E., Rosario, A.S., Tirmarche, M., Tomáscaron, L., Whitley, E. and Wichmann, H.E. (2005) Radon in Homes and Risk of Lung Cancer: Collaborative Analysis of Individual Data from 13 European Case-Control Studies. *BMJ*, **330**, Article 223. https://doi.org/10.1136/bmj.38308.477650.63

[8] United Nations Scientific Committee on the Effects of Atomic Radiation (2000) Sources and Effects of Ionizing Radiation. United Nations Publication, New York.

[9] Ali Yalim. H., Gümüş, A. and Ünal, R. (2018) Determination of Indoor Radon Concentration and Effective Dose Equivalent at Workplaces of Afyonkarahisar Province. *Süleyman Demirel University Faculty of Arts and Sciences Journal of Science*, **13**, 29-35. https://doi.org/10.29233/sdufeffd.442298

[10] Hashim, A.K., Awad, E.I. and Mezher, H.A. (2017) Measurement of Annual Effective Dose for RADON in Kerbala University Campus, Freiha, Iraq. *Iraqi Journal of Public Health*, **1**, 21-25.

[11] Al-Kazwini, A.T., Al-Arnaout, M.M. and Abdulkareem, T.R. (2020) Radon-222 Exposure and Dose Concentration Levels in Jordanian Dwellings. *Journal of Environmental and Public Health*, **2020**, Article ID: 6668488. https://doi.org/10.1155/2020/6668488

[12] Yarahmadi, M., Shahsavani, A., Mahmoudian, M.H., Shamsedini, N., Rastkari, N. and Kermani, M. (2016) Estimation of the Residential Radon Levels and the Annual Effective Dose in Dwellings of Shiraz, Iran, in 2015. *Electronic Physician*, **8**, 2497-2505. https://doi.org/10.19082/2497

[13] Aghdam, M.M., DaPelo, S., Dentoni, V., Fanti, V., Bernardini, A., Randaccio, P. and Chiriu, D. (2019) Measurements of Indoor Radon Levels and Gamma Dose Rates. *Proceedings of the 5th World Congress on New Technologies* (*NewTech*'19), Lisbon, August 2019, ICEPR 149.

[14] Amin, S.A., Alalgawi, S.D. and Hashimn, H.M. (2015) Indoor Radon Concentrations and Effective Dose Estimation in AlKarkh Side of Baghdad Dwellings. *Iranian Journal of Science & Technology*, **39**, 491-495. http://ijsts.shirazu.ac.ir

[15] Abd-Elmoniem Ahmed, E. (2014) A Study of Indoor Radon Levels and Radon Effective Dose in Dwellings of Some Cities of Gezira State in Sudan. *Nuclear Technology & Radiation Protection*, **29**, 307-312. https://doi.org/10.2298/NTRP1404307E

[16] Canadian Nuclear Safety Commission (CNSC) (2011) Radon and Health. Catalogue Number CC172-67/2011-PDF.

[17] International Commission on Radiological Protection (2007) The 2007 Recommendations of the International Commission on Radiological Protection. https://journals.sagepub.com/doi/pdf/10.1177/ANIB_37_2-4

[18] Blanchardon, E., Laurier, D., Paquet, F. and Lecomte, J.F. (2009) Dosimétrie du radon: Les points de vue de l'UNSCEAR et de la CIPR sont-ils contradictoires? *Radioprotection*, **44**, 207-216. https://doi.org/10.1051/radiopro/2009007

[19] International Commission on Radiological Protection (1993) Protection against Radon-222 at Home and Work. A Report of a Task Group of the International Commission on Radiological Protection. *Annals of the ICRP*, **23**, 1-45. https://journals.sagepub.com/doi/pdf/10.1177/ANIB_23_2

[20] Kitson-Mills, D., Sovoe, S., Opoku-Ntim, I., Kyei, K.A., Marnotey, S., Anim-Sampong, S., Kwabeng, M.A., Otoo, F. and Baiden, F. (2019) An Assessment of Indoor Radon Level in a Suburb of Ghana. *Environmental Research Communications*, **1**, Article ID: 061002 https://doi.org/10.1088/2515-7620/ab2af7

[21] Idriss, H., Salih, I. and Elzain, A.E.A. (2020) Environmental Radon Mapping in Sudan, Orderly Review. *Journal of Taibah University for Science*, **14**, 1059-1066. https://doi.org/10.1080/16583655.2020.1798586

[22] Choukri, A. and Hakam, O.K. (2019) Equivalent Doses of Indoor 222Rn in Some Dwellings and Workspaces in Morocco. International Radiation Protection Association. https://www.irpa.net/members/P10.65FP.pdf

[23] Wang, H., Zhang, L., Gao, P. and Guo, Q.J. (2022) A Pilot Survey on Indoor Radon Concentration in Beijing. *Radiation Medicine and Protection*, **3**, 22-25. https://doi.org/10.1016/j.radmp.2022.01.003