Seasonal Indoor Radon Assessment and Estimation of Cancer Risk: A Case Study of Obafemi Awolowo University Nigeria

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ABSTRACT: Human exposure to indoor radon has been a subject of continuous concern due to its health implications, especially as it relates to lung cancer. Radon contaminates indoor air quality and poses a significant health threat if not abated/controlled. A seasonal indoor radon assessment of residential buildings of Obafemi Awolowo University was carried out to determine radon seasonal variability and to evaluate the cancer risk to the residents. AT-100 diffusion-based track detectors were deployed within living rooms and bedrooms for the radon measurement. During the rainy season, the average indoor radon concentration was 18.4 ± 10.1 Bq/m^3, with higher concentrations observed in bedrooms compared to living rooms, whereas the average radon concentration was 19.0 ± 4.4 Bq/m^3 in the dry season, with similar radon levels in living rooms and bedrooms. The potential alpha energy concentration values ranged from 1.62 to 7.57 mWL. The annual effective dose equivalent values were below the world average and recommended limits for public exposure. Of the three geological units underlying the residences, the buildings overlying the granite gneiss lithology have the highest radon concentrations with average value of 21.4 Bq/m^3. The soil gas radon concentration to indoor radon concentration ratio over the granite gneiss lithology is 0.006. The estimated average lifetime cancer risk due to radon inhalation in the residences indicated a potential risk of cancer development in 178 persons in 100 000 population over a lifetime period. The average indoor radon concentrations were below the recommended limit, requiring no immediate remediation measures. Improved ventilation of residential apartments is recommended to minimize residents' risk to indoor radon.

KEYWORDS: Improved ventilation, indoor air quality, lung cancer and other respiratory diseases, radiation, radon

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Introduction

Human exposure to indoor radon has been a subject of continuous concern due to its health implications, especially as it relates to lung cancer. Radon gas is a naturally occurring radioactive element that is produced in the ground and can diffuse into the indoor environment. Within the indoor environment, the gas can accumulate to potentially hazardous levels. Radon is colorless and odorless. It exists naturally in three isotopes. They are: ^{219}Rn ($t_{½}$ = 3.96 seconds), ^{220}Rn ($t_{½}$ = 56.6 seconds), and ^{222}Rn ($t_{½}$ = 3.82 days). Due to the relatively short half-lives of ^{219}Rn and ^{220}Rn, they do not travel far in the air.[1] However, ^{222}Rn is of significant importance from a radiation protection perspective as it contributes to about 50% of human exposure to natural radiation.[2] The radon gas that is produced due to the natural decay of uranium present in soil and rock formations permeates into buildings, particularly through cracks in foundations, gaps within and around pipes, spaces between floor tiles, holes within concrete blocks, and other openings. However, there are other sources of radon exhalation into the indoor air. These include the rocks, soil, and other building materials used in the building construction.[3,4] Underground water used for domestic purposes also contributes to the radon burden in homes.[5]

Prolonged radon inhalation has been established as the second leading cause of lung cancer after cigarette smoking.[6,7] Radon and its radioactive decay products emit alpha particles, which have the potential to damage lung tissues when inhaled. Prolonged exposure to high levels of radon increases the risk of developing lung cancer, especially among smokers. When radon is inhaled, it deposits its decay products within the respiratory tract. The radon decay products are alpha particle emitters. The released alpha particles with high linear energy transfer can cause cellular damage to the lung tissue and consequently initiate the development of lung cancer. The damage is a result of oxidative damage to DNA, proteins, and lipids from ionizing alpha particles. The aggregation of these cellular damages may result in malignancy.[8]

The plausibility of non-lung cancer effects from radon inhalation has been indicated by researchers. The risk of skin cancer, stomach cancer, central nervous system cancer, breast cancer, esophageal cancer, oropharyngeal cancer, kidney cancer, leukemia, thyroid cancer, and lymphoma in relation to radon inhalation has been studied.[9,10] Other non-cancer health effects of radon have been suggested. High levels of indoor radon exposure have been associated with non-cancer diseases including respiratory, nervous system and cardiovascular system diseases.[11] However, further research is needed to establish these connections conclusively.

To minimize the deleterious health effect of radon, regulatory agencies and global health institutions advise and/or provide regulations on the permissible limits of radon in indoor air. The maximum permissible level of indoor radon established by the US Environmental Protection Agency (USEPA) is 148 Bq.m^{-3} (4 pCi/L) above which mitigation is advised to reduce the radon level in existing building.[12] The World Health Organization (WHO) recommends a reference level of 100 Bq m^{-3}.[13] The International Commission on Radiological Protection (ICRP) also recommended an annual radiation dose from radon inhalation in range of 3 to 10 mSv as a basis for adopting action levels for intervention in dwellings.[14]

To determine the radiation exposure of members of the public to indoor radon, long-term passive radon detectors are usually deployed for measurement. This method has been widely used all across the world for different radon studies.[15-17]

The aim of this study is to assess the seasonal indoor radon in the residential buildings of Obafemi Awolowo University and to evaluate the cancer risk due to the radon exposure. The living room and the bedroom being the mostly occupied rooms in a building have been selected for the study. The study area which is underlain with diverse geological formations,[18,19] will provide a new perspective on indoor radon distribution in a heterogeneous geological environment.

Owing to the sparseness of data on seasonal variation of indoor radon in Nigeria, Obafemi Awolowo University (OAU) provides an ideal setting for seasonal measurement of indoor radon being an academic area where the residents are assumed to be aware of the deleterious effect of radon compared to non-academic areas. Also, the OAU residential area is underlain with three lithological units. Therefore, the study of seasonal indoor radon in the residential buildings of OAU will provide crucial information about the prevalence and distribution of radon in buildings underlain with heterogenous geology. This will enable policymakers to develop strategies for radon mitigation targeted at public health protection in the institutions, and by extension in public residential buildings. The study also provides a platform for informed decision-making regarding building regulations, construction practices, and the implementation of radon mitigation measures.

Methodology

The study area

The study area is the Obafemi Awolowo University residential quarters. The site was chosen for study owing to its distinct situation of three different lithologic units.[19-21] Also, indoor studies are relatively easier to conduct in an academic area where residents cooperate more with researchers. The area is located in the Southwest area of Nigeria within the basement complex formations. The area lies on the granite gneiss, mica schist, and migmatite gneiss lithologies. The geographical coordinates of the area lie between 7°30′43″ and 7°32′24″ on the North and within and 4°32′55″ on the East. The area is characterized by two distinct seasons—rainy (April–October), and dry (November–March) seasons.[22] While the rainy season is usually overcast, the dry season is muggy and partially cloudy. The average diurnal temperature of the area varies between 22 and 33°C , and precipitation between 0.2 and 8.5 mm day^{-1}.

Table 1. Typical building characteristics of the study area.

FLOOR DIMENSION (M^2)	15.3
Volume (m^3)	43.4
Wall area (m^2)	35.1
Floor area (m^2)	15.3
Window area (m^2)	7.8
Ratio of window to wall area (%)	22.3
Ratio of window to floor area (%)	51.3

Building characteristics

A typical building in the study area has a large garden, servant quarters, and a main building. The main building has a living room, kitchen, study, and 1 or 2 toilets. The exterior and interior walls are made of concrete blocks of 225 and 150 mm respectively. The windows have steel louver blade timber frames. The internal doors are wooden while the exit doors are either steel or metal-framed glass. The roofs are made of asbestos-corrugated ceilings with asbestos. All the windows in the apartments tested have openings perpendicular to the prevailing wind. Most of the occupants practice natural ventilation (i.e. opening of their windows for almost 24 hours a day). Although the apartments have central air conditioning installed in the 70s, they are all in a state of moribund as at the period of study. The typical physical characteristics of the residential buildings including wall-window area ratio and wall-floor ratio are presented in Table 1. The architectural sketch of a typical residential building in the area is presented in Figure 1.

Data collection and radon measurement

Based on accessibility of sampled buildings and other limitations in the study area, 25 buildings were sampled in the rainy season, while 20 buildings were sampled in the dry season. A total of 45 buildings were sampled for the 2 seasons. The activity concentrations of radon (^{222}Rn) in indoor air were measured using the AccuStar AT-100 Alpha Track radon

Figure 1. Architectural sketch of a typical building in the study area.

detector. Measurements for rainy (April–October) and dry (November–March) seasons were carried out to determine the seasonal variation of radon in indoor air. A total of 90 detectors were deployed for measurement—50 and 40 for rainy and dry seasons respectively. In each of the sampled houses, two detectors were used—one in the living room and the other in the bedroom.

The AT-100 radon monitor is a diffusion-based track detector. The device is built with a rugged casing to filter out dust particles and radon progeny through a filter that is incorporated into the casing. The casing is molded from electrically conducting plastic to minimize electrical charge effects from the positively charged radon progeny generated inside the detector. The hemispheric design of the base of the detector allows for the maximization of the sensitivity of the detector and uniformity in the distribution of the particles for more efficient counting. The track detector foil, 2.3 cm × 5.3 cm in dimension, is typically laser cut and is housed within the sturdy casing. The foil is imprinted with a batch number for ease of identification. The detector is calibrated and receives its calibration factor. Pre-casing background track checks are typically conducted on the detector. The general specifications quoted by the manufacturers are: rereads −2% of the original mean, coefficient of variation −5%, up to 10 000 countable tracks per foil, uncertainty −15% for a 90-day 148 Bq/m^3 exposure, and the lower limit of detection is 29.6 Bq/m^3 per month. Upon deployment for measurement, it was ensured that the detectors were hung at least 1 m away from the doors, walls, and windows. An average distance of 1.5 m breathing height for a sitting adult was maintained for the detectors while also ensuring a minimum distance of 0.7 m from the ceiling. At the end of a minimum of 90-day deployment, the detectors were harvested and sealed in an air-tight polythene sample bag to prevent the formation of new tracks on the detector. The detectors were subsequently transported to the laboratory for analysis. At the laboratory, the detectors were electrochemically etched under laboratory standard conditions to process their alpha tracks. The alpha tracks were counted with computer-aided image analysis equipment.

Indoor radon distribution map

The distribution map of radon in the dwellings of Obafemi Awolowo University Staff Quarters was prepared using ArcGIS software (ESRI, USA, version 10). High-resolution satellite imagery of OAU was gotten from Google Earth online. The imagery was re-georeferenced. The coordinates of houses sampled were captured by the American version of Global Navigation Satellite systems that is, GPS-Global Positioning Systems. The house location coordinates were overlayed on the vectorized/digitized imagery. A spatial distribution analysis of Radon concentration was performed.

Calculations

The radon concentration (Bq/m^3) was estimated from the track densities produced on the detector using the following expression[23,24]:

$$C_{Rn} = \frac{TD}{F_{cal} \times t} \tag{1}$$

where TD (tracks mm^{-2}) is the track density, F_{cal} (tracks mm^{-2} hr^{-1}(1.843 kBq m^{-3})$^{-1}$) is the calibration factor and t is the exposure time. The potential alpha energy concentration (PAEC) is often used as a concentration term in working level (WL) which accounts for the contributions of all the alpha-emitting progenies of ^{222}Rn. 1 WL is the amount of radon decay product that will produce activity of 100 pCi/L (i.e. 3700 Bq/m^3). It is calculated using the following expression:

$$PAEC = \frac{F_{eq} \times C_{Rn}}{3700} \tag{2}$$

where F_{eq} is the equilibrium factor given as 0.4 (UNSCEAR[2]), C_{Rn} is the radon concentration in Bq/m^3. Also, the Working Level Month (WLM) is estimated to account for exposure over an indoor occupancy hour within a month. It is computed with the following expression (Obed et al[25]):

$$WLM\left(y^{-1}\right) = \frac{H\left(hr\, y^{-1}\right)}{170\left(hr\right)} \times PAEC \tag{3}$$

where $H = 7008hr = \left(24 \times 365 * 0.8\right)hr$ is the indoor occupancy hours per year with the assumption that 0.8 fraction of time is spent indoors,[2] and 170 hours is the number of hours in a working month based on 8 hours a day for 21 working days per month.

Results and Discussion

Seasonal variation of indoor radon

The indoor radon concentration, potential alpha energy concentration (PAEC), working level month (WLM), annual effective dose equivalent, and excess lifetime cancer risk due to radon inhalation obtained during the rainy season and dry season are presented in Tables 2 and 3, respectively. The indoor radon concentration in the rainy season ranges from 15.0 Bq/m^3 to 70.0 Bq/m^3 with an average value of 18.4 ± 10.1 Bq/m^3. Within the living rooms, the radon activity concentrations range from 15.0 Bq/m^3 to 33.0 Bq/m^3 with an average value of 16.5 ± 3.8 Bq/m^3. Within the bedrooms, the radon activity concentration range from 15.0 Bq/m^3 to 70.0 Bq/m^3 with an average value of 20.2 ± 13.6 Bq/m^3. Generally, the radon activity concentrations in the twenty-five houses sampled during the rainy season have higher concentrations in the bedrooms than in the living rooms except in three locations (R8, R21, and R25). The frequency distribution of radon concentration for the rainy season is shown in Figure 2. The distribution indicates that most of the measured radon activities lie between the concentrations of 0to 15 Bq m^{-3}. Nineteen rooms each for the living room and bedroom have radon concentrations within the range which represents 76% of all the radon measurements during the rainy season. Five rooms have radon concentration in the range of 16to 30 Bq m^{-3} in the living room, whereas there are three in the bedroom within the concentration range. The distribution indicates higher radon concentrations in the bedroom.

In the dry season, the measured radon concentrations vary from 15 Bq/m^3 to 33 Bq/m^3 with an overall average of 19.0 ± 4.4 Bq/m^3. In the living room, the radon concentration was within this concentration range, but with an average value of 19.3 ± 4.6 Bq/m^3. However, in the bedroom, the concentrations vary from 15 Bq/m^3 to 30 Bq/m^3 with an average value of 18.7 ± 4.2 Bq/m^3. The frequency distribution of radon concentrations obtained for the dry season is shown in Figure 3. The modal values of the radon concentrations lie in the range of 16to 30 Bq m^{-3}, with the living room and bedroom having frequencies of 12 and 11 respectively. However, in the concentration range of 0to 15 Bq m^{-3}, the frequencies are 7 and 9 respectively.

Table 2. Radon concentrations, annual effective dose equivalent (AEDE), excess lifetime cancer risk (ELCR), and room dimensions for the rainy season.

LIVING ROOM								BED ROOM							
ROOM CODE	RADON CONC. (BQ/M^3)	PAEC (MWL)	WLM (Y^{-1})	AEDE (MSV/Y)	ELCR (10^{-3})	VOL. OF ROOM (M^3)	TOTAL AREA OF OPENINGS (M^2)	ROOM CODE	RADON CONC. (BQ/M^3)	PAEC (MWL)	WLM (Y^{-1})	AEDE (MSV/Y)	ELCR (10^{-3})	VOL. OF ROOM (M^3)	TOTAL AREA OF OPENINGS (M^2)
R1A	15	1.622	0.183	0.380	1.460	34.7	11.5	**R1B**	15	1.622	0.183	0.380	1.460	70.2	6.9
R2A	15	1.622	0.183	0.380	1.460	98.0	14.5	**R2B**	15	1.622	0.183	0.380	1.460	34.7	6.0
R3A	33	3.568	0.403	0.830	3.200	37.7	3.4	**R3B**	70	7.568	0.855	1.760	6.790	37.7	3.4
R4A	15	1.622	0.183	0.380	1.460	116.1	14.4	**R4B**	15	1.622	0.183	0.380	1.460	34.7	6.0
R5A	15	1.622	0.183	0.380	1.460	116.1	16.5	**R5B**	15	1.622	0.183	0.380	1.460	44.4	5.2
R6A	15	1.622	0.183	0.380	1.460	126.4	11.7	**R6B**	15	1.622	0.183	0.380	1.460	44.4	5.4
R7A	15	1.622	0.183	0.380	1.460	116.1	21.0	**R7B**	15	1.622	0.183	0.380	1.460	43.9	5.2
R8A	18	1.946	0.220	0.450	1.750	116.1	17.9	**R8B**	15	1.622	0.183	0.380	1.460	34.7	5.6
R9A	15	1.622	0.183	0.380	1.460	116.1	21.0	**R9B**	15	1.622	0.183	0.380	1.460	43.9	5.2
R10A	15	1.622	0.183	0.380	1.460	102.9	13.3	**R10B**	15	1.622	0.183	0.380	1.460	37.7	7.1
R11A	15	1.622	0.183	0.380	1.460	116.1	21.0	**R11B**	15	1.622	0.183	0.380	1.460	43.9	5.2
R12A	15	1.622	0.183	0.380	1.460	105.6	18.1	**R12B**	30	3.243	0.366	0.760	2.910	43.9	5.2
R13A	15	1.622	0.183	0.380	1.460	105.6	17.7	**R13B**	59	6.378	0.720	1.490	5.720	43.9	5.2
R14A	15	1.622	0.183	0.380	1.460	158.8	12.0	**R14B**	15	1.622	0.183	0.380	1.460	39.7	3.4
R15A	15	1.622	0.183	0.380	1.460	114.5	12.1	**R15B**	15	1.622	0.183	0.380	1.460	44.4	4.4
R16A	18	1.946	0.220	0.450	1.750	114.5	12.1	**R16B**	22	2.378	0.269	0.550	2.130	44.4	4.4
R17A	22	2.378	0.269	0.550	2.130	116.1	12.1	**R17B**	22	2.378	0.269	0.550	2.130	44.4	4.4
R18A	15	1.622	0.183	0.380	1.460	241.7	11.7	**R18B**	15	1.622	0.183	0.380	1.460	188.3	9.2
R19A	15	1.622	0.183	0.380	1.460	288.2	21.2	**R19B**	15	1.622	0.183	0.380	1.460	35.6	7.2
R20A	15	1.622	0.183	0.380	1.460	159.5	17.6	**R20B**	18	1.946	0.220	0.450	1.750	63.8	5.1
R21A	18	1.946	0.220	0.450	1.750	109.7	3.2	**R21B**	15	1.622	0.183	0.380	1.460	109.7	2.4
R22A	15	1.622	0.183	0.380	1.460	115.5	11.7	**R22B**	15	1.622	0.183	0.380	1.460	34.7	6.0
R23A	15	1.622	0.183	0.380	1.460	144.4	18.8	**R23B**	15	1.622	0.183	0.380	1.460	62.9	12.9
R24A	15	1.622	0.183	0.380	1.460	109.6	16.0	**R24B**	15	1.622	0.183	0.380	1.460	50.2	5.7
R25A	18	1.946	0.220	0.450	1.750	158.8	12.0	**R25B**	15	1.622	0.183	0.380	1.460	40.0	3.4
MIN	15	1.622	0.183	0.380	1.460	34.7	3.2		15	1.622	0.183	0.380	1.460	34.7	2.4
MAX	33	3.568	0.403	0.830	3.200	288.2	21.2		70	7.568	0.855	1.760	6.790	188.3	12.9
MEAN	16.5	1.782	0.201	0.416	1.603	125.6	14.5		20.2	2.188	0.247	0.511	1.967	52.6	5.6
STD DEV	3.8	0.407	0.046	0.094	0.363	50.3	4.7		13.6	1.467	0.166	0.341	1.315	31.8	2.0

Table 3. Radon concentrations, annual effective dose equivalent (AEDE), excess lifetime cancer risk (ELCR), and room dimensions for dry season.

LIVING ROOM								BED ROOM							
ROOM CODE	RADON CONC. (BQ/M^3)	PAEC (MWL)	WLM (Y^{-1})	AEDE (MSV/Y)	ELCR (10^{-3})	VOL. OF ROOM (M^3)	TOTAL AREA OF OPENINGS (M^2)	ROOM CODE	RADON CONC. (BQ/M^3)	PAEC (MWL)	WLM (Y^{-1})	AEDE (MSV/Y)	ELCR (10^{-3})	VOL. OF ROOM (M^3)	TOTAL AREA OF OPENINGS (M^2)
R1A	15	1.622	0.183	0.380	1.460	115.5	11.7	**R1B**	22	2.378	0.269	0.550	2.130	34.7	6.0
R2A	15	1.622	0.183	0.380	1.460	158.8	12.0	**R2B**	15	1.622	0.183	0.380	1.460	39.7	3.4
R3A	18	1.946	0.220	0.450	1.750	37.7	3.4	**R3B**	15	1.622	0.183	0.380	1.460	37.7	3.4
R4A	15	1.622	0.183	0.380	1.460	159.5	17.6	**R4B**	18	1.946	0.220	0.450	1.750	63.8	5.1
R5A	18	1.946	0.220	0.450	1.750	37.7	3.4	**R5B**	15	1.622	0.183	0.380	1.460	37.7	3.4
R6A	18	1.946	0.220	0.450	1.750	114.5	12.1	**R6B**	18	1.946	0.220	0.450	1.750	44.4	4.4
R7A	22	2.378	0.269	0.550	2.130	109.7	3.2	**R7B**	22	2.378	0.269	0.550	2.130	37.7	3.4
R8A	33	3.568	0.403	0.830	3.200	37.7	3.4	**R8B**	18	1.946	0.220	0.450	1.750	37.7	3.4
R9A	18	1.946	0.220	0.450	1.750	241.7	13.9	**R9B**	15	1.622	0.183	0.380	1.460	188.3	3.4
R10A	15	1.622	0.183	0.380	1.460	37.7	3.4	**R10B**	15	1.622	0.183	0.380	1.460	37.7	3.4
R11A	26	2.811	0.317	0.660	2.520	109.7	3.2	**R11B**	22	2.378	0.269	0.550	2.130	37.7	3.4
R12A	22	2.378	0.269	0.550	2.130	22.4	4.9	**R12B**	22	2.378	0.269	0.550	2.130	23.3	3.4
R13A	15	1.622	0.183	0.380	1.460	159.5	17.6	**R13B**	30	3.243	0.366	0.760	2.910	63.8	5.1
R14A	22	2.378	0.269	0.550	2.130	37.7	3.4	**R14B**	15	1.622	0.183	0.380	1.460	37.7	3.4
R15A	18	1.946	0.220	0.450	1.750	109.7	3.2	**R15B**	22	2.378	0.269	0.550	2.130	37.7	3.4
R16A	15	1.622	0.183	0.380	1.460	288.2	21.2	**R16B**	15	1.622	0.183	0.380	1.460	35.6	7.2
R17A	22	2.378	0.269	0.550	2.130	158.8	12.0	**R17B**	15	1.622	0.183	0.380	1.460	39.7	3.4
R18A	22	2.378	0.269	0.550	2.130	288.2	21.2	**R18B**	18	1.946	0.220	0.450	1.750	35.6	7.2
R19A	22	2.378	0.269	0.550	2.130	288.2	21.2	**R19B**	15	1.622	0.183	0.380	1.460	35.6	7.2
R20A	15	1.622	0.183	0.380	1.460	37.7	3.4	**R20B**	26	2.811	0.317	0.660	2.520	37.7	3.4
MIN	15	1.622	0.183	0.380	1.460	22.4	3.2		15	1.622	0.183	0.380	1.460	23.3	3.4
MAX	33	3.568	0.403	0.830	3.200	288.2	21.2		30	3.243	0.366	0.760	2.910	188.3	7.2
MEAN	19.3	2.086	0.236	0.485	1.874	127.5	9.8		18.7	2.016	0.228	0.470	1.811	47.2	4.3
ST.DEV	4.6	0.492	0.056	0.114	0.438	88.1	6.9		4.2	0.459	0.052	0.106	0.409	33.6	1.4

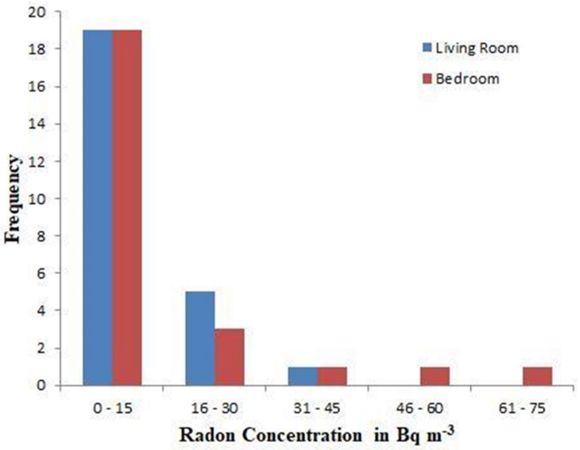


Figure 2. Frequency distribution of indoor radon concentration in rainy season.

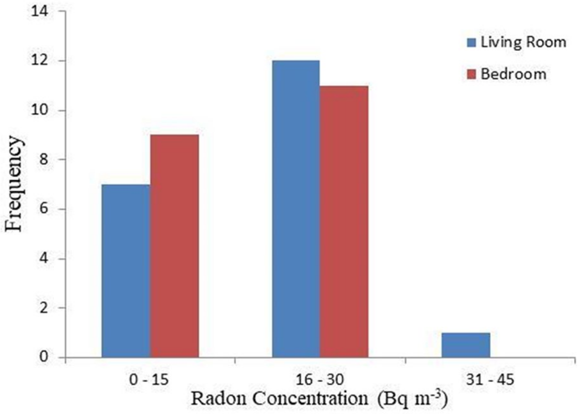


Figure 3. Frequency distribution of indoor radon concentration in dry season.

The indoor radon concentration obtained in this study has been compared with the concentration values obtained in other studies in the West African region with similar climate. The comparison is presented in Supplemental Table. In the present study, average radon concentration obtained showed a relatively higher concentration during the dry season. Although, this is a departure from results from many other studies, these average values are not significantly different. Survey of similar seasonal indoor radon studies conducted in a tropical region like the present study area shows higher radon concentration during the rainy season.[26-29] Other non-seasonal studies carried out in the region as presented in the Table covering Nigeria and Cameroon shows higher order of indoor radon concentration ranging from 2 to 10.[30-34] All these studies, including the present study highlighted the influence of meteorological parameters on the indoor radon concentrations. The anomaly obtained in the seasonal radon concentrations obtained in this study can be attributed to the meteorological conditions and the residents' ventilation practice.

The statistics of the radon concentration values obtained across both rainy and dry seasons are presented in Table 4. The geometric mean of the radon concentrations across the two seasons is 17.7 ± 8.1 Bq/m^3 while the median and mode of the distribution are the same (15 Bq/m^3). The skewness value is 4.4. The value suggests that the data distribution is highly positively skewed. Similarly, the kurtosis value of 23.3 indicates that the distribution is peaked and with fatter tails.

Table 4. The statistics of radon concentration values.

STATISTIC	VALUE
Number of observations	90
Minimum (Bq/m^3)	15
Maximum (Bq/m^3)	70
Arithmetic mean (Bq/m^3)	18.6
Geometric mean (Bq/m^3)	17.7
Median (Bq/m^3)	15
Mode (Bq/m^3)	15
Standard deviation (Bq/m^3)	8.1
Skewness	4.4
Kurtosis	23.3

Across the two seasons, the average radon concentration is higher in the bedroom than in the living room with values of 19.5 ± 10.5 Bq/m^3 and 17.7 ± 4.4 Bq/m^3 respectively (Table 5). This is in agreement with the study by Aladeniyi et al[30] conducted in some other parts of Southwest Nigeria. This is attributable to the area of openings (window and door openings) in the living room. The average areas of opening for the houses sampled for the two seasons are 12.4 ± 6.2 m^2 and 5.0 ± 1.9 m^2 for the living room and bedroom respectively. This is indicated by the strong negative correlation of −0.47 between the area of openings in the living room and radon concentration. Also, air exchange from the outdoors and the living room occasioned by more access opportunities is a factor. A similar result was obtained in a survey of homes in the UK.[35] Since most houses have more window fittings in the living room than the bedroom, as seen in the sampled apartments, this can explain the observed differences. Moreover, radon concentration is expected to be lower in areas with improved ventilation than in areas with poor ventilation. Similar findings were also reported in previous studies in Nigeria where the living room had the lowest radon concentrations compared with other places.[25,36,37] The average radon concentration obtained in this study is much less than the average radon concentration (255 Bq/m^3) reported in the Oke-Ogun region with similar geology.[23] The main reason attributable to this is the higher ventilation due to the building characteristics of the area typically with large window areas. Architectural designs of buildings in an academic environment often provide for adequate ventilation.[38]

Table 5. The statistics of radon concentration and room parameters.

STATISTIC	LIVING ROOM			BED ROOM		
	RADON CONC. (BQ/M³)	VOL. OF ROOM (M³)	TOTAL AREA OF OPENINGS (M²)	RADON CONC. (BQ/M³)	VOL. OF ROOM (M³)	TOTAL AREA OF OPENINGS (M²)
Min	15.0	22.4	3.2	15.0	23.3	2.4
Max	33.0	288.2	21.2	70.0	188.3	12.9
Mean	17.7	126.4	12.4	19.5	50.2	5.0
Std Dev	4.4	69.7	6.2	10.5	32.7	1.9

Table 6. The correlation coefficient of indoor radon concentration with room parameters.

	CORRELATION (*R*)	REMARKS
Radon conc. and Area of Openings in Rooms	−0.290 (P = .04*)	An inverse relationship exists and is also Significant (P < .05)
Radon Level and Volume of Rooms	−0.231 (P = .10)	An inverse relationship exist but is not significant (P > .05)

Table 7. Ratio of soil gas radon to indoor radon concentration across the lithologic units of the study area.

LITHOLOGY	MEAN OF SOIL GAS RADON CONC. (BQ/M³)	MEAN OF INDOOR RADON CONCENTRATION (BQ/M³)	RATIO OF SOIL GAS TO INDOOR RADON CONCENTRATIONS
Granite gneiss	3508.2	21.4 ± 12.2	0.0060 (0.6%)
Banded gneiss	11 500.3	18.3 ± 11.9	0.0016 (0.16%)
Mica schist	28 366.9	15.6 ± 1.3	0.0005 (0.05%)

More generally, the correlation between indoor radon concentrations and room parameters (living room and bedroom) is presented in Table 6. The correlations between indoor radon concentration and the area of openings (windows and doors) and volume of rooms of sampled residences in the study area indicate that an inverse relationship (negative correlation, $r = -0.290$) exists between the area of openings in buildings and indoor radon and the relationship is also significant ($P = .04$). Also, the correlation between the room volume and indoor radon concentration indicates that an inverse relationship ($r = -0.231$) exists between the two variables, however, the correlation is not significant ($P = .10$).

The window-to-wall ratio and window-to-floor ratio of the most sampled apartment are >30 % compared to the conventional residential buildings. All the sampled houses in both seasons have concentrations far below the W.H.O.'s recommended limit of 100 Bq/m³. Even in areas designated as high radon potential zones from the previous study through soil gas radon mapping,[18] the indoor radon concentrations were below the limit. Another physical characteristic of the buildings which influenced the indoor radon concentration is the window openings on opposite walls. The windows have been designed such that one is windward and the other is opposite allowing for ventilation maximization.

Radon distribution based on underlying lithology

The distribution of indoor radon based on the heterogeneity of the underlying geology of the study was assessed. The distribution of the 45 sampled houses in the rainy season is such that 23, 9, and 13 houses were sampled over banded gneiss, granite gneiss, and mica schist respectively. The average indoor radon concentrations over the three lithologies as presented in Table 7 are 18.3±11.9 Bq m^{-3}, 21.4 ± 12.2 Bq m^{-3}, and 15.6 ± 1.3 Bq m^{-3} respectively. The mean plot of the indoor radon concentrations across the three lithologic units of the study area is shown in Figure 4. The highest indoor radon concentration obtained over the granite gneiss lithology can be attributed to the richness of uranium—a parent radionuclide of radon in granitic rocks. The spatial distribution of the indoor radon concentration over the lithological units of the study area is presented in Figure 5. The figure shows how the 90 radon measurements in the 45 sampled buildings are spatially distributed over the three lithologic units of the area. The radon concentration levels have been

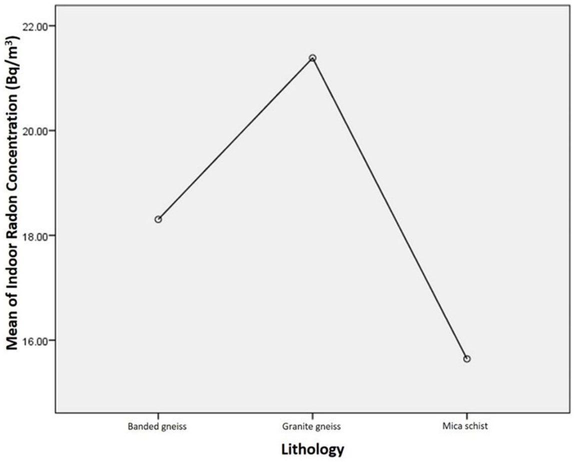


Figure 4. Average Indoor Radon concentration over the Lithologies.

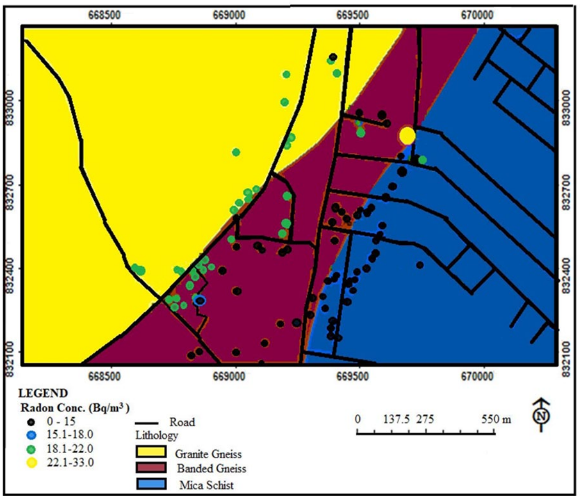


Figure 5. Spatial distribution of indoor radon concentration over lithological units.

color-coded into four concentration bands: 0to 15.0 Bq/m^3 (black), 15.1to 18.0 (blue), 18.1to 22.0 (green), and 22.1to 33.0 (yellow).

The soil gas from the underlying geology of an environment is the major contributor to indoor radon concentration.[39,40] Based on the Authors' previous research[18] on the radon in soil gas of the environment, the current study attempts to compare the average radon concentration in the underlying geology of the environment with the average indoor radon concentration. The ratios of soil gas concentration to indoor radon across the three lithologic units are shown in Table 7. As shown in the table, the indoor radon concentration is not proportionate to the soil gas radon concentration. This indicates that other factors affecting radon concentration indoors such as ventilation and area of pore spaces are dominant. The estimated percentage contributions of soil gas radon to the indoor radon concentrations as shown in the table are 0.6%, 0.16%, and 0.05% for granite gneiss, banded gneiss, and mica schist respectively, assuming that other factors are negligible. By implication, these percentages suggest that a soil gas radon concentration of 1000 Bq m^{-3} will contribute 6 Bq m^{-3}, 1.6 Bq m^{-3}, and 0.5 Bq m^{-3} of indoor radon concentrations in the three lithologies respectively.

Potential alpha energy concentration (PAEC) and working level month (WLM)

The evaluated PAEC values for all the sampled rooms as presented in Table 8 in the rainy season vary from 1.622 to 7.568 mWL with an average value of 1.985 mWL. In the dry season, the PAEC values range from 1.622 to 3.568 mWL with an average of 2.051 mWL. The distribution of PAEC in the sampled apartments is as shown in Figure 6. The figure indicates that the highest concentrations in the range between 1.51and 2.00 mWL with a percentage distribution of 86% (Figure 6a) and 62.5% (Figure 6b) for the rainy and dry seasons respectively. The WLM estimated for the rainy season ranges from 0.183 year^{-1} to 0.855 year^{-1} with an average of 0.224 year^{-1} as presented in Table 8. However, for the dry season, the range and average are 0.183 year^{-1} to 0.403 year^{-1} and 0.232 year^{-1} respectively. The PAEC and the WLM values remain within the admissible limits.

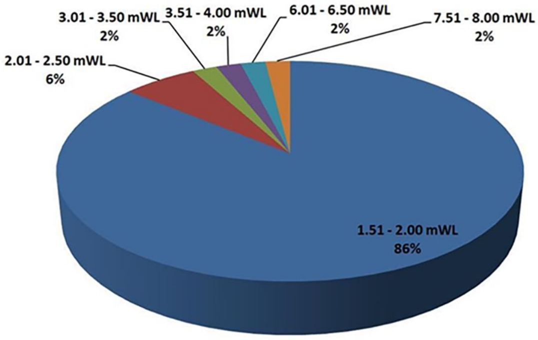
Annual effective dose and cancer risk

The annual effective dose equivalent (AEDE) values for all the rooms in the rainy season vary from 0.38 to 1.76 mSv year^{-1} with the average value of 0.46 ± 0.25 mSv year^{-1}, while the values vary from 0.38 to 0.76 mSv year^{-1} for the dry season with the average of 0.48 ± 0.11 mSv year^{-1} (Table 8). The average AEDE values for the living rooms and bedrooms are 0.42 ± 0.49 mSv year^{-1} and 0.51 ± 0.34 mSv year^{-1} respectively for the rainy season (Table 2), while the values are 0.49 ± 0.11 mSv year^{-1} and 0.47 ± 0.11 mSv year^{-1} respectively for the dry season (Table 3). Overall, the estimated AEDE values from all measurements range from 0.38 to 1.76 mSv year^{-1} with an average value of 0.47 ± 0.20 mSv year^{-1}. These values are less than the world average values of 1.15 mSv year^{-1} reported in UNSCEAR[2]. Also, the values are below the recommended limit of 4 mSv recommended for members of the public.[41,42]

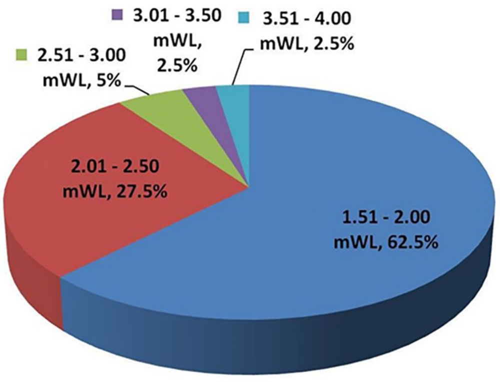
The evaluated excess lifetime cancer risk (ELCR) to humans due to human occupation of the rooms (90 rooms) in the area in the rainy season ranges from 1.46×10^{-3} to 6.79×10^{-3} with an average value of $\left(1.78\pm0.98\right)\times10^{-3}$ (Table 8). This average value indicates the risk of 178 persons developing cancer over a lifetime period in a population size of 100 000. In the living rooms, the values range from 1.46×10^{-3} to 3.20×10^{-3} with an average value of $\left(1.60\pm0.37\right)\times10^{-3}$, whereas, in the bedroom, the value varies from 1.46×10^{-3} to 6.79×10^{-3} with an average value of $\left(1.96\pm1.32\right)\times10^{-3}$.

Table 8. The statistics of the PAEC, WLM, AEDE and ELCR in the rainy and dry seasons.

SEASON	STATISTIC	PAEC (MWL)	WLM (YEAR^{-1})	AEDE (MSV/YEAR)	ELCR (10^{-3})
Rainy Season	Min	1.622	0.183	0.38	1.46
	Max	7.568	0.855	1.76	6.79
	Average	1.985	0.224	0.46	1.78
	Std Dev	1.096	0.124	0.25	0.98
Dry Season	Min	1.622	0.183	0.38	1.46
	Max	3.568	0.403	0.83	3.20
	Average	2.051	0.232	0.48	1.84
	Std Dev	0.477	0.054	0.11	0.43
Overall	Min	1.622	0.183	0.38	1.46
	Max	7.568	0.855	1.76	6.79
	Average	2.015	0.228	0.47	1.81
	Std Dev	0.877	0.099	0.20	0.79



(a) PAEC (Rainy Season)



(b) PAEC (Dry Season)

Figure 6. Pie chart showing the distribution of potential alpha energy concentration in rainy and rainy seasons. (a) PAEC (rainy season). (b) PAEC (dry season).

Similarly, the average ELCR values obtained for the dry season in the living rooms and bedrooms are $(1.87 \pm 0.44) \times 10^{-3}$ and $(1.81 \pm 0.41) \times 10^{-3}$ respectively with an overall average value of $(1.84 \pm 0.43) \times 10^{-3}$.

Conclusion

The seasonal variation of radon within the residential buildings of the OAU which lies on a heterogeneous geology was assessed. A total of 90 measurements within the living rooms and bedrooms of the OAU was carried out during both the rainy and dry seasons. The results show higher radon concentrations in the dry season with the bedrooms exhibiting higher concentrations. Generally, the area of openings in the buildings is found to significantly influence the indoor radon concentration with a negative correlation observed between both parameters. In all of the residences, ventilation practice has been observed as a significant determinant for indoor radon concentration. All radon concentration measurements were below the World Health Organization's recommended exposure limit. Since there are no lower limits for which radon exposure does not pose a cancer risk, a cancer risk of 178 cancer cases per 100 000 population over a lifetime was evaluated for the study area. The study has also provided baseline indoor radon concentrations delineation over the underlying geology of the area. The results obtained in this study will contribute to the development of a national radon map for Nigeria and study data will provide a basis for the development of regulatory limits aimed at public radiation protection. Accessibility to homes for indoor radon study is a challenge in the area due to the low level of awareness and education on radon. This requires future intensive awareness programs which can be undertaken by relevant Government Agencies and Non-Governmental Organizations. Further study on indoor radon in the study area is recommended to correlate age of building, construction model and construction materials with indoor radon concentration.

List of abbreviations

AT-100: Alpha track detector
WL: Working Level
WLM: Working Level Month
PAEC: Potential Alpha Energy Concentration
AEDE: Annual Effective Dose Equivalent
ELCR: Excess Lifetime Cancer Risk

Author Contribution Statement

D.T.E and R.O designed the study. Y.A and D.T.E wrote the first draft of the manuscript. D.T.E, B.B.O and J.E.T implemented the research. D.T.E, Y.A, B.B.O, R.O and J.E.T managed the literature searches. Y.A, D.T.E and B.B.O analyzed the data. All authors read and approved the final manuscript.

Availability of Data and Materials

All data generated or analyzed during this study are included in this published article.

Supplemental Material

Supplemental material for this article is available online.

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