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Location Based Approach to Determining the Effective Dose from Radon Concentrations in Residential Environments

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ABSTRACT: In this study, measurements of indoor radon concentrations were undertaken, and the annual effective dose to the residents relative to both general and field occupancy were estimated. The measurements were carried out in residential environments of Lagos Nigeria using CR-39 solid state nuclear track detectors. The detectors were mounted in ninety-eight different rooms within the selected buildings at approximate height of 2 m above the ground and exposed for a period of six months. Data were obtained from the residents with the use of semi-structured self-administered questionnaire. The indoor occupancy hour of 9.8, 1.8, 2.9 and 6.6 were recorded for bedroom, bathroom/ toilet, kitchen and living room respectively in the study area. The maximum and minimum occupancy factor recorded were 96% and 76% respectively from the data obtained. The dose received by a resident, ranged from 150.2 – 222.3 μSvy^{-1} and 166.7 – 185.3 μSvy^{-1} computed with the field occupancy factors and the general occupancy factor respectively.

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Ingestion and inhalation of naturally occurring radionuclides give rise to radiation dose which varies considerably depending on the location, occupancy time, diet and dwelling of the individual (UNSCEAR, 2006; Martin *et al*., 2012; Abodunrin and Akinloye, 2020). Estimates of the proportion of lung cancers attributable to radon, a naturally occurring radionuclide, range from 3% to 14%, depending on the method of calculation (WHO, 2010). Exposures of individuals within a building may also differ. Certain residents of every dwelling occupy the house for longer periods. For instance the elderly, and particularly women who normally spend more time indoors than any other occupants, are prone to more exposures to indoor radon. As many people are exposed to low and moderate levels, the majority of lung cancers related to radon are caused by the chronic exposures rather than the acute exposures to higher concentrations (WHO, 2010). Effective dose is accepted and applied internationally as the central radiological protection quantity, and has proven to be a valuable and robust quantity for use in the optimization of protection and setting of control criteria: limits, constraints, and reference levels (Harrison *et al*., 2015). In many radiological studies, the effective dose is always estimated using the occupancy factor of 80% for indoors and 20% for outdoors in accordance with International Commission on Radiological Protection, ICRP, (ICRP, 1993 & 2007) and United Nation Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) reports (UNSCEAR, 2001 & 2017). These known occupancy factors which may otherwise be referred to as general occupancy factors may not be sufficient to reflect the variation of occupancy time with location, type of building, health status, occupation, age, gender etc. There are concerns which border on how representative is the occupancy factor being deployed in the estimation of annual effective dose from different environments. Additionally, it has been noted that the factor depends on occupants' habits, occupational structure and the prevailing weather conditions, the reason for which (Arogunjo *et al*., 2004; Tzivaki and Waller, 2018) adjudged it a location

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specific parameter. The knowledge of the population habits in a study area in terms of location and occupancy is crucial in determining the occupancy factors required for effective dose calculations.

In the investigation of naturally occurring radioisotopes of terrestrial origin, the knowledge of outdoor and indoor occupancy factors establishes the basis for the assessment of doses to the population (Brown, 1983). The study, Arogunjo *et al*. (2004), for instance, re-evaluated the occupancy factors for effective dose estimated in tropical environment, and recorded outdoor occupancy factor of 0.3 for rural dwellers and 0.22 for urban dwellers. These values were observed to be 50% and 10% respectively above the world average of 0.2 from UNSCEAR. Another study, Arogunjo and Adekola, (2007) developed a model to examine the occupancy factor for atmospheric radiation exposure by urban as well as rural dwellers. From the findings, an average city dweller spent 20.3% of the 24 hours each day exposed to radiation from the atmosphere as an average rural dweller on the other hand spent 26.9% being exposed to atmospheric radiation. The model remarkably revealed the necessity to evaluate the indoor and outdoor occupancy factor of any given environment with a view to assessing the definite doses of radiation exposure to the population. A study on occupancy factor model for exposure to natural radionuclides along the coastline of Erongo Region, Namibia has also recorded an indoor occupancy factor of 0.52 and outdoor occupancy factor of 0.48 (Onjefu *et al.*, 2006). This study aims to determine the occupancy factor for the residential environments within the study area, estimate the annual effective dose from radon exposure to occupants of the study area by applying the general occupancy factor and field occupancy factor.

MATERIALS AND METHODS

A total of ninety-eight (98) rooms were randomly selected within the typical residential environments of Lagos State. These locations are generally coastal areas and most of the residents have their business(es) in the vicinity of their homes. Hence more people stay indoors. A semi-structured self-administered questionnaire was employed for data collection. Questions were drawn based on the stated objective of this study. Data were drawn from those who occupy each residence most. This study did not involve the collection of personally identifiable information. The study protocol was reviewed by the Ladoke Akintola University of Technology Department of Pure and Applied Physics Institutional Review Board and exempted from the need for ethical approval. Also written informed consent was obtained from all study participants. Radon measurements were carried out using 1 by 1 cm CR-39 solid state nuclear track detectors mounted in each sampling location at a height of approximately 2 m above the floor representing the typical breathing zone (Health Canada, 2008). After six (6) months of exposure the detectors were withdrawn, kept separately in aluminum foil and taken to the laboratory. The measurement was made with solid state nuclear track detector CR-39 for six months in order to obtain the long term average, the protocol, which has been validated in literatures (WHO, 2010; ICRP, 1993; Abodunrin and Akinloye, 2020; Matiullah, 2013). The widely accepted method for obtaining long-term radon concentrations average is the use of track detectors (WHO, 2010; ICRP, 1993; Abodunrin and Akinloye, 2020). The detectors were etched with 6.25 M of Sodium Hydroxide (NaOH) solution at 70 ºC for 3 hours, washed with running water and soaked in distilled water for approximately 10 and 15 minutes respectively, in order to remove the etchant residue from the etched pits. Thereafter, they were dried in the laboratory at room temperature (Abodunrin and Akinloye, 2020). The tracks on the detectors were counted using an image analysis system consisting of Charge Coupled Devices (CCD) camera connected to a personal computer (PC) and an optical microscope of 40x objective lens. Radon concentration, C_{Rn}, was computed using equation 1.

$$C_{Rn} = \frac{T_D(\text{track.mm}^{-2}) \times CF(\text{Bqhm}^{-3}/\text{track.mm}^{-2})}{T(h)} \quad (1)$$

Where CF (kBqh m^{-3}/track.mm^{-2}) represents the calibration factor, T is the exposure time in h and T_D is the track density in track.mm^{-2} (Matiullah, 2013).

The calibration factor supplied by the manufacturer remains valid not later than six months of delivery, within which the detectors were exposed in this study. The background counting was obtained from the average track density from detectors etched before field installation and after retrieval from sampling location. This value was deducted from each measurement. The procedure employed in this study to measure radon (Rn-222) using CR-39 involved the application of diffusion chambers which were made of conductive plastics. Throughout the measurement period, the detector was kept in tamper-proof, RSKS standard type diffusion chamber as specified and supplied by the manufacturer. This ensures that the radon isotopes actinon, ^{219}Rn, with a half-life of 3.96 s and thoron, ^{220}Rn, with a half-life of 55.6 s do not contribute to the measurement.

Derivation of Occupancy Factor for the Study Area: The occupancy factor for the study area was derived using equation 2.

$$Occupancy\ factor\ (\%) = \frac{mean\ daily\ occupancy\ (h)}{24\ h} \times 100\ (\%) \qquad (2)$$

Estimation of Annual Effective Dose from Radon: The effective dose attributable to radon exposure in the study area was estimated using;

$$H_E(Svy^{-1}) = C_{Rn} \times E_{Rn} \times T \times DCC \qquad (3)$$

Where radon equilibrium factor (indoor), $E_{Rn} = 0.4$, dose conversion coefficient, $DCC = 9\ nSv/Bqhm^{-3}$ [1, 17], and T (hy^{-1}), the occupancy time is given as:

$$T = occupancy\ factor \times 24\ h \times 365.25 \qquad (4)$$

RESULTS AND DISCUSSION

Each day, the residents spend an average of 8.79, 1.67, 1.60 and 6.25 hours in the bedroom, bathroom/toilet, kitchen and living room respectively in Badagry (Table 1), 10.00, 2.22, 2.67 and 8.06 hours respectively in Epe as well as 10.50, 1.50, 4.50 and 5.50 hours in Ikorodu. These imply an average occupancy time of 9.76, 1.80, 2.92 and 6.60 hours in the bedroom, bathroom/ toilet, kitchen and living room respectively for the study area. These correspond to an indoor occupancy factor of 87.85% which is in excess of the general occupancy factor by 8. The results from this study suggest that, on average, residents spend more time in the indoor environment. Also, it was observed that the occupancy factor varies from one environment to another with the highest value being 95.63% and the lowest being 76.26%. Three issues may be noted for further investigations. One, the data was obtained from member of each residence that stays indoor most. Most of the residents have their petty trades some spaces within the house. The questionnaires were distributed on the bases of one per each residence; and a total of ninety-eight (98) residences were surveyed. However, the outdoor occupancy data was not collected. Secondly, factors associated with time spent indoors such as personal properties (like sex, age, occupation), climate, living area (rural vs. urban), etc were not adjusted in evaluating the field occupancy factors. Lastly, more bedrooms were investigated in Bagdary (47%) compared to Epe (23%) and Ikorodu (36%). The authors acknowledge this bias. This however was due to the level of support from the volunteers; as more volunteers were receptive to the idea of having the detectors in their bedroom in Badagry than in Ikorodu and Epe area.

Annual Effective Dose: The descriptive statistics of the results obtained for annual effective dose (H_e) estimated from the concentrations of radon in the indoor environments are as shown in Table 2. The annual effective dose due to indoor radon exposure using the general occupancy factor of 80% range from 141.63 – 219.14 µSvy^{-1} with a mean of 166.69 ± 26.22 µSvy^{-1} for Badagry, 174.45 – 188.34 µSvy^{-1} with a mean of 183.60 ± 4.58 µSvy^{-1} for Epe, and 207.01 – 164.86 µSvy^{-1} with a mean of 185.31 ± 16.16 µSvy^{-1} for Ikorodu. The mean for the study area is 714.13 ± 31.58 µSvy^{-1} which is lower than the global average of 1.15 mSvy^{-1} (UNSCEAR, 2000) and the lower limit of the recommended action level of 3 – 10 mSvy^{-1} (ICRP, 1993). The result implies that the dose to the residents of the study area, attributable to radon exposure, is at safe level.

Effect of Occupancy Factor on the Annual Effective Dose Estimates: The effects of occupancy factor on annual effective dose determined by employing the general occupancy factor of 0.8 and the on-field occupancy factor per room for the study area are as indicated in Table 2.

The dose to a resident at general occupancy factor is greater in the bedroom, bathroom/ toilet, kitchen and living room by approximate factors in the order of 2.0, 11.5, 12.0 and 3.0 respectively for Badagry, 1.9, 8.6, 7.0 and 2.0 respectively for Epe, as well as 1.8, 12.8, 4.0 and 3.0 respectively for Ikorodu. The results showed that, a resident receives total dose of 666.75 µSvy^{-1}, 734.41 µSvy^{-1} and 741.23 µSvy^{-1} for Badagry, Epe and Ikorodu respectively using general occupancy factor, which is greater than the dose at corresponding field occupancy factors by approximate factors in the order of 4.4, 3 and 3.6 respectively.

Findings from this study suggest that radiological studies employing the general occupancy factor may require adjustment for particular location, corroborating Arogunjo *et al*. (2004) and Tzivaki and Waller (2018). It may not be accurate to assume for each of the 4 room categories an occupational factor of 0.8 (who stays 80% of his time in the bathroom/toilet, for instance). Analysis based on the total dose may not subsist in reality.

Table 1: Derived Indoor Occupancy Factor for the Study Area

Room	Badagry			
	Number of Rooms	Occupancy Hour	Mean Occupancy Hour	Occupancy Factor (%)
Bedroom	14	123	8.79	36.61
Bathroom/ Toilet	3	5	1.67	6.94
Kitchen	5	8	1.60	6.67
Living Room	8	50	6.25	26.04
Total	30	186	18.30	76.26
	Epe			
	Number of Rooms	Occupancy Hour	Mean Occupancy Hour	Occupancy Factor (%)
Bedroom	9	90	10.00	41.67
Bathroom/ Toilet	9	20	2.22	9.26
Kitchen	6	16	2.67	11.11
Living Room	16	129	8.06	33.59
Total	40	255	22.95	95.63
	Ikorodu			
	Number of Rooms	Occupancy Hour	Mean Occupancy Hour	Number of Rooms
Bedroom	10	105	10.50	43.75
Bathroom/ Toilet	6	9	1.50	6.25
Kitchen	4	18	4.50	18.75
Living Room	8	44	5.50	22.92
Total	28	176	22.00	91.67

Table 2: Estimates of Effective Dose (μSvy^{-1}) at different Occupancy (OCC) Factors

Location / **Room**	**Badagry**				
				H_e (μSvy^{-1})	
	Mean Rn (Bqm^{-3})	**Mean OCC (hour)**	**Field OCC Factor**	**Field OCC**	**0.8 OCC**
Bedroom	5.93	8.79	36.61	68.51	149.71
Bathroom/ Toilet	8.68	1.67	6.94	19.02	219.14
Kitchen	5.61	1.60	6.67	11.80	141.63
Living Room	6.19	6.25	26.04	50.87	156.27
Total	26.41	18.30	76.26	150.20	666.75
Mean	6.60	4.58	19.06	37.55	166.69
	Epe				
	Mean Rn (Bqm^{-3})	**Mean OCC (hour)**	**Field OCC Factor**	**H_e (μSvy^{-1})**	**Mean Rn (Bqm^{-3})**
Bedroom	7.43	10.00	41.67	97.70	187.58
Bathroom/ Toilet	7.29	2.22	9.26	21.30	184.04
Kitchen	6.91	2.67	11.11	24.22	174.45
Living Room	7.46	8.06	33.59	79.09	188.34
Total	29.09	22.95	95.63	222.31	734.41
Mean	7.27	5.74	23.91	55.58	183.60
	Ikorodu				
	Mean Rn (Bqm^{-3})	**Mean OCC hour**	**Field OCC Factor**	**H_e (μSvy^{-1})**	
				Field OCC	**0.8 OCC**
	6.53	10.50	43.75	90.16	164.86
	6.87	1.50	6.25	13.55	173.44
	8.20	4.50	18.75	48.52	207.02
	7.76	5.50	22.92	56.12	195.91
	29.36	22.00	91.67	208.35	741.23
	7.34	5.50	22.92	52.09	185.31

The means of 37.55 μSvy^{-1} and 166.69 μSvy^{-1} were obtained respectively with field occupancy factors and general occupancy factor for Badagry; 55.58 μSvy^{-1} and 183.60 μSvy^{-1} respectively for Epe; 52.09 μSvy^{-1} and 185.31 μSvy^{-1} respectively for Ikorodu. These expressions likewise indicate higher average annual effective dose to the exposure of the residents with the general occupancy factor. The mean computed with the field occupancy factor in this scenario implies that the resident is exposed in only one room per day. The means of 37.55 μSvy^{-1} and 166.69 μSvy^{-1} were obtained respectively with field occupancy factors and general occupancy factor for Badagry; 55.58 μSvy^{-1} and 183.60 μSvy^{-1} respectively for Epe; 52.09 μSvy^{-1} and 185.31 μSvy^{-1} respectively for Ikorodu. These expressions likewise indicate higher average annual effective dose to the exposure of the residents with the general occupancy factor. The mean computed with the field occupancy factor in this scenario implies that the resident is exposed in only one room per day.

This analysis does not also represent the true situation. Further analysis of the results indicate that a resident with an average indoor occupancy factor of 76% (field) and 80% experience an exposure of 150 μSvy^{-1} and 166.69 μSvy^{-1} respectively in Badagry; 222.31 μSvy^{-1} and 183.60 μSvy^{-1} respectively at average indoor occupancy of 95.63% (field) and 80% in Epe; 208.35 μSvy^{-1} and 185.31 μSvy^{-1} respectively at average indoor occupancy of 91.67% (field) and 80% in Ikorodu. This analysis suffices for the facts that the resident occupies the four rooms at different times within this indoor hours/ periods (total value computed with field occupancy factor is required for this analysis) and that the sum of all categories is 0.8 (hence the mean computed with the general occupancy factor is applicable).

It may then be stated that though the general occupancy results in overestimations in some area, the field occupancy reveals higher annual exposure dose.

Conclusion: Measurements of indoor radon concentrations were carried out in order to evaluate effective dose. Indoor occupancy factor of 87.85% obtained is in excess of general occupancy factor by approximate value of 8, suggesting residents spend more time indoor than what general occupancy factor may account for. Also, it was observed that occupancy factor varies across locations. In many cases, the results revealed higher effective dose with field occupancy factor representing actual experience of the residents. Therefore, this study suggests a location based approach in the estimation of effective dose for radiological evaluations.

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