Nigerian Journal of Physics (NJP)

ISSN: 1595-0611

Volume 32(2), June 2023

Assessment of Radon Gas in Some Selected Areas in Makurdi Metropolis

***Akaagerger, N. B., Kaki, D. K., Shiada, M. S. and Akpenwuan, E. A.**

Department of Physics Benue State University Makurdi-Nigeria

*Corresponding author's email: bnguvan@gmail.com

ABSTRACT

Radon gas levels were evaluated to determine the exposure rate in Makurdi and surrounding areas due to the lack of available data on radon levels. The study utilized a digital radon detector to measure indoor radon concentrations in selected areas of Makurdi Metropolis. Forty-one (41) offices/houses were chosen for indoor radon measurements using the digital radon detector (model QRI: dimensions 120 mm x 69 mm x 25.5 mm), known for its portability and ability to provide precise readings within 24 hours. Measurements were conducted during the dry season, showing average indoor and outdoor radon gas concentrations at Benue State University of 18.50 ± 3.70 Bq/m3 and 14.43 ± 0.37 Bq/m3, respectively. The overall indoor radon concentration in Makurdi was found to be 12.23 ± 1.68 Bq/m3, all below the recommended limits by ICRP for residential buildings (200 Bq/m3 and 600 Bq/m3). The annual absorbed dose rate ranged from 0.29 to 0.46 mSv/yr within the school environment and 0.22 to 0.36 mSv/yr outside the school, with an overall mean of 0.31 ± 0.01 mSv/yr. These values are below the ICRP intervention limit (3-10 mSv/yr) and within the acceptable value of 2.4 mSv/yr. However, poorly ventilated offices may pose potential health risks due to radon gas effects.

Keywords:
Radon Concentration,
Environmental indoor,
Digital machine.

INTRODUCTION

Radon is a noble gas according to the periodic table. It does not interact with other compounds (very few chemical removal processes occur) and tends to travel a significant distance in air, water or soil, especially if the soil is porous (Cember & Thomas, 2000). At a standard temperature and pressure (STP) of around 1.217kg/m^3 at sea level, the density of radon is about 8 times that of the earth's atmosphere. This makes radon gas stand out, being the heaviest among the other noble gases (Celen et al., 2023). Radon comes naturally from the parent, radionuclide radium 226, and from the uranium-238 breakdown series, it is the fifth. It takes 3.8 days for it to lose half of its activity in the environment, thereby making it easier to diffuse through the soil, even into the air before decaying by emitting alpha particles (Darby et al., 2005). Radon has three natural isotopes, namely, radon-222, radon-220 and radon-219 (^{222}Rn, ^{220}Rn and ^{219}Rn). ^{222}Rn is the most stable isotope among them. The common earth's radioactive elements are Uranium and thorium, with long half-lives ranging from about three minutes to 4.4 billion years, as a result, radon will remain in ages to come due to the generation from its ore (US EPA, 2014). Relatively high levels of radon emissions are associated with particular types of bedrock and unconsolidated deposits. Uranium concentration also sometimes occurs in limestone, sedimentary ironstone, and permeable sandstone (Appleton, 2007). However, areas having a higher concentration of uranium in their soil and rocks beneath may record a low indoor radon concentration in their dwellings. On the other hand, those dwellings where the soil and rocks beneath contain low uranium concentrations can have high indoor radon concentrations.

In the 2000s, alum shale was discovered in some building materials in which a high amount of radium was found (Appleton, 2007; Hahn et al., 2015). Aside from the indoor radon generated by these building materials, radon infiltration through soil was also discovered as an additional source of radon. Outdoor radon also adds up to indoor radon, but its concentration is of minor importance (WHO, 2007). Natural energy sources such as gas and coal used for cooking were also found to contain traces of Uranium-238. Water stored in dwellings, also adds up to the high health risk of indoor radon inhalation in homes (Hopke et al., 2000). Radon can also be found in well water which is used in various ways by individuals at home; for bathing, washing of clothes, and dishes, flushing of toilet and something drinking. In carrying out these activities, radon is released from the water and contributes to health hazards. UNSCEAR established that the progenies of radon, for example, Pb and Po discharge along the inner walls of the thoracic which serves as the entry point of the bronchial epithelium (Kendall & Smith, 2002; UNSCEAR, 2000) for this reason, countries worldwide have reasoned together for standardized radon concentration levels above which measures are taken (WHO, 2007). Numerous studies have been done globally to determine radon levels.

Figure 1 represents research carried out which shows that, under normal conditions, more than 70% of the total annual dose received by people originates from different sources of ionizing radiation. Forty per cent is due to inhalation and ingestion of natural radioactive radon gas (^{222}Rn) and its bye product. Exposure to radon via inhalation especially in closed rooms is the cause of about 10% of all death from lung cancer. Changes at the cellular and molecular levels are significantly more pronounced in the early stage of life. The emission percentage of radon into the atmosphere coming from a few meters above the ground is at least 80% (WHO, 2007). Two-thirds of the average annual exposure is due to external exposure (Wang, 2002). Inhalation of radon gas and its daughters will expose the lung tissue to short-lived alpha-emitting radionuclides, which will increase the risk of lung cancer. Kidney-related diseases have also been observed in some people exposed to radon. The reason is that the Kidney receives the highest dose compared to other body organs after radon is transferred from the lung to the kidney by blood (CHEN et al., 2018).

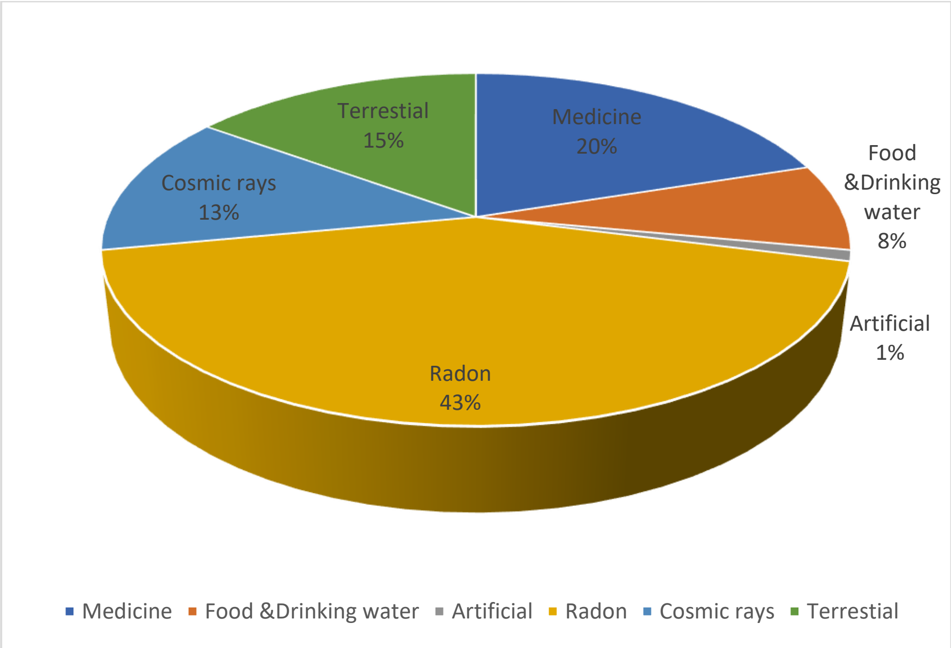

Figure 1: Estimate of total Annual Dose revealed by people (WHO, 2007)

Due to its gaseous nature, radon may be released from soil material to the environment, and it is therefore present not only in soil or rock but also in air and water. All radon isotopes are radioactive. The half-life of ^{222}Rn is 3.8 days, which is long enough to allow much of the gas to escape from the upper layer of the soil and reach the atmosphere. Substantially less of the ^{220}Rn and ^{219}Rn reach the air because of their short half-lives (56 and 4s respectively).

Different sources are responsible for the presence of radon and its daughters in houses. The sources of radon gas are the building materials and their components, groundwater, and soil. The radiological impact of radon is due to radiation exposure of the body by the gamma rays and irradiation of the lung tissues from inhalation of radon and its progeny. From the natural risk point of view, it's necessary to know the dose limit of public exposure and to measure the natural environmental radiation level provided by ground, air, water, foods, buildings interiors etc. for estimation of the exposure to natural radiation source. Hence, the study was conducted to assess the indoor radon gas levels in selected areas of Makurdi.

MATERIALS AND METHODS

A digital radon detector sensitive to alpha particles was utilized in this investigation. The detector sensor consists of a passive diffusion chamber, which allows air samples to flow into it. A photodiode located inside this chamber counts the amount of "daughter" radon particles in the air sample. The readings are averaged over time. The short-term average was used in calculating radon exposure. The short-term average shows radon readings for one day, updated every hour. For each office, readings were taken for the occupancy duration, which spanned from 9 am to 4 pm.

The detector was normally placed in the office to represent the air that was breathed in the office. The monitor was not exposed to direct sunlight or electromagnetic radiation. It was positioned lying flat at least 25 cm from the nearest wall, at least 50 cm above the floor, and at least 150 cm from the nearest door, window, or ventilation device. Cardboard paper was glued to the wall and used to hold the detectors in place.

The monitor was normally left untouched for the duration of the measurements. It was hung on the walls about 1.5 m from the floor in the dwellers' offices. The 1.5 m was assumed to be an average respiratory level. The upper surface (some offices placed on the table) which remains highly sensitive was freely revealed or exposed so that it was able to record the alpha particles released because of radon decomposition in the offices and rooms within Benue State University Makurdi and other locations within Makurdi metropolis. In each office, the detector was kept for two days, and the study lasted from November 2022 to February 2023, representing the dry season.

The detector was also placed at the Boys Hostel at Benue State University Makurdi. It was fixed in the bathrooms of the inhabitants.

The unit of the indoor radon gas concentration value obtained with the monitor is in pCi/L. The average value of the radon is then converted to the required unit of Bq/m3. This can be done by multiplying the average value by 37, and the annual dose and effective dose of radon were calculated using the formula below;

$$Annual\ dose\ for\ Radon\ (mSv/yr) = \sum C_{RN} \times D \times F \times \quad (1)$$

Where C_{Rn} is the effective dose received by an adult per ^{222}Rn unit of air volume. It is a constant with value 9.0 x 10^{-6} mSv/hr per Bq/m

T is the indoor radon occupancy factor given as = 0.4

Where 0.4 is from 9 hrs/24 hrs

F is the equilibrium factor for radon. It is a constant value of 0.8

D is the average dose measured in Bqm$^{\mathbf{3}}$

The effective dose is calculated from the annual effective dose using the formula.

$$E = \sum W_T\ Q_{TR} \quad (2)$$

Where

$$Q_{TR} = W_R \times D_A \quad (3)$$

$$Annual\ Effective\ Dose = W_T \times W_R\ D_A \quad (4)$$

W_R is the radiation weighting factor. For alpha particles = 20

W_T is the tissue weighting factor. For lung = 0.12 (Bushberg et al., 2002)

RESULTS AND DISCUSSION

The results of indoor radon concentration levels as measured from different locations in some selected hot spots in Makurdi Local Government are presented in Table 1 – 6.

Table 1: Radon Concentration with Annual Effective Dose Rate (AEDR) from the (BSU) First Campus

Offices	Min. (Bq/m^3)	Max. (Bq/m^3)	Mean Radon Conc.$\pm$ Standard Deviation (Bq/m^3)	Nature of Ventilation	AEDR (mSv/yr)
SIWES Office	11.84	14.80	13.33 $\pm$ 1.48	Ventilated	0.34
Physics Lab	14.80	19.24	17.02 $\pm$ 2.22	Ventilated	0.43
I.C.T	11.10	11.84	11.84 $\pm$ 0.51	Ventilated	0.30
Maths & Comp	7.40	11.84	9.62 $\pm$ 2.22	Ventilated	0.24
New Physics Lab	11.47	17.70	14.62 $\pm$ 3.14	Ventilated	0.37
Labor Mkt	7.40	8.14	7.77 $\pm$ 0.37	Not properly Ventilated	0.20
Kinetics	14.06	15.54	14.80 $\pm$ 0.74	Not properly Ventilated	0.37
Chemistry	11.47	14.06	12.77 $\pm$ 1.30	Ventilated	0.32

At BSU's first campus, there are mostly cemented, tiled, painted, zinc roofing, and aluminium sheet houses and these are old houses, the highest average indoor radon mean concentration is 17.02 $\pm$2.22 Bq/m^3 with the highest annual effective dose of 0.43 mSv/yr which is from the Physics Lab because of the nature of the building (poor ventilation and cracked on the walls).

Table 2: Radon Concentration with AEDR from the Hostel's (BSU) First Campus

Rooms (Bq/m^3)	Min. (Bq/m^3)	Max. Standard Deviation	Mean Radon Conc.$\pm$ (Bq/m^3)	Nature of Ventilation	AEDR (mSv/yr)
<u>Boys Hostel</u>					
B. Room 1	14.80	22.20	18.50 $\pm$ 3.70	Not properly Ventilated	0.46
B. Room 2	13.32	14.06	13.69 $\pm$ 0.37	"	0.34
B. Room 3	8.88	11.10	9.99 $\pm$ 1.11	"	0.25
B. Room 4	7.40	10.36	8.88 $\pm$ 1.48	"	0.22
B. Room 5	7.40	10.36	8.88 $\pm$ 1.48	"	0.22
B. Room 6	14.80	17.76	16.28 $\pm$ 1.76	"	0.41
<u>Girls Hostel</u>					
G. Room 7	11.10	11.84	11.47 $\pm$ 0.37	"	0.28
G. Room 8	10.73	11.47	11.10 $\pm$ 0.37	"	0.28
G. Room 9	8.88	10.36	9.62 $\pm$ 0.52	"	0.24

At BSU Hostels there are cemented, tiles, painted, zinc roofing, and aluminium sheet houses and these are old houses, the highest average indoor radon mean concentration is 18.50 $\pm$ 3.70 Bq/m^3 with the highest annual effective dose of 0.46 mSv/yr from boy's hostel bathroom because of poor ventilation.

Table 3: Radon Concentration with AEDR from some selected places (BSU) Campus

Offices	Min. (Bq/m^3)	Max. (Bq/m^3)	Mean Radon Conc.$\pm$ Standard Deviation (Bq/m^3)	Nature of Ventilation	AEDR (mSv/yr)
Main Library	11.10	12.58	11.84 $\pm$0.74	Ventilated	0.29
College of Sc.	14.80	16.65	15.73 $\pm$ 0.92	Ventilated	0.40
Law Office 1	11.84	13.32	12.58 $\pm$ 0.74	Ventilated	0.32
Law Office 2	15.54	15.91	15.73 $\pm$0.18	Ventilated	0.39
Labour Mkt Second Campus	14.84	17.76	14.80 $\pm$2.10	Not Properly Ventilated	0.37
Library Second Campus	11.10	11.84	11.47 $\pm$ 0.37	Ventilated	0.28

At BSU Campus, there are mostly cemented, tiles, painted, zinc roofing, and aluminium sheet houses and these are old houses, the highest average indoor radon mean concentration is 15.73 $\pm$ 0.18 Bq/m^3 with the highest annual effective dose of 0.40 mSv/yr from the college of health science hostel (ventilation is poor).

Table 4: Radon Concentration with AEDR from some selected places at (BSUTH)

Offices	Min. (Bq/m^3)	Max. (Bq/m^3)	Mean Radon Conc.$\pm$ Standard Deviation (Bq/m^3)	Nature of Ventilation	AEDR (mSv/yr)
Hematology	11.84	14.06	12.95 $\pm$ 1.11	Ventilated	0.33
Radiology 1	11.10	11.10	11.47 $\pm$ 0.37	Ventilated	0.29
Radiology 2	11.47	14.80	13.13 $\pm$ 1.67	Ventilated	0.33
Admin. 1	7.40	10.36	8.88 $\pm$ 1.48	Ventilated	0.22
Admin. 2	11.47	17.76	11.47 $\pm$ 3.15	Ventilated	0.28
Admin. 3	14.80	17.76	16.24 $\pm$ 1.76	Ventilated	0.41

At BSUTH Makurdi, there are mostly cemented, painted, zinc roofing, and aluminium sheet houses and these are old houses, the highest average indoor radon mean concentration is 16.24 $\pm$ 1.76 Bq/m^3 with the highest annual effective dose of 0.41 mSv/yr from the administrative block (some cracks on the wall and poor ventilation).

Table 5: Radon Concentration with AEDR from some selected places in Makurdi Local Government Area of Benue State

Houses	Min. (Bq/m^3)	Max. (Bq/m^3)	Mean Radon Conc.$\pm$ Standard Deviation (Bq/m^3)	Nature of Ventilation	AEDR (mSv/yr)
North Bank				Not properly	
House 1	14.06	14.80	14.43 $\pm$ 0.37	Ventilated	0.36
House 2	9.25	9.99	9.26 $\pm$ 0.37	Ventilated	0.23
House 3	11.10	16.28	13.69 $\pm$ 2.30	Ventilated	0.34
High Level					
House 1	13.69	17.76	13.32 $\pm$ 2.40	Ventilated	0.33
House 2	8.88	17.76	9.81 $\pm$ 2.03	Ventilated	0.25
House 3	7.77	11.84	12.21 $\pm$ 0.37	Ventilated	0.31
Coca Cola					
House 1	11.84	12.58	12.95 $\pm$ 1.11	Ventilated	0.32
House 2	10.36	14.06	12.58 $\pm$ 2.22	Ventilated	0.31
House 3	11.10	14.80	12.95 $\pm$ 1.85	Ventilated	0.32
House 4	11.84	14.80	13.32 $\pm$ 1.48	Ventilated	0.33
House 5	11.10	19.24	11.84 $\pm$ 0.51	Ventilated	0.29
House 6	7.39	11.10	8.88 $\pm$ 1.10	Ventilated	0.22

At Tilley Gyado College North Bank, Cocoa Cola, High-Level Makurdi, there are mostly Burnt brick houses, cement blocks, zinc roofing, aluminium sheet houses and mostly painted and good ventilation, the highest average indoor radon mean concentration is 14.43 $\pm$ 0.37 Bq/m^3 with the highest annual effective dose as 0.36 mSv/yr from house 1 North Bank (not properly ventilated and wracks on the wall with poor ventilation).

Table 6: Cumulative Mean Concentration, Standard Deviation, and AEDR for the various locations

Locations	Sampling Point	Cumulative Radon mean Conc. Standard Deviation (Bq/m3).	Cumulative AEDR (mSv/yr)	ICRP mSv/yr
First Campus	8	11.31 $\pm$1.33	0.33	
Hostel (Boys/Girls)	9	12.04 $\pm$1.24	0.30	
Second Campus	6	14.13 $\pm$0.84	0.34	
BSUTH	6	11.58 $\pm$1.55	0.29	**3-10**
Other Areas	12	12.13 $\pm$2.18	0.27	
Mean	**41**	**12.23 $\pm$ 1.43**	**0.31**	

These tables are summarized in the figures below using a bar chart.

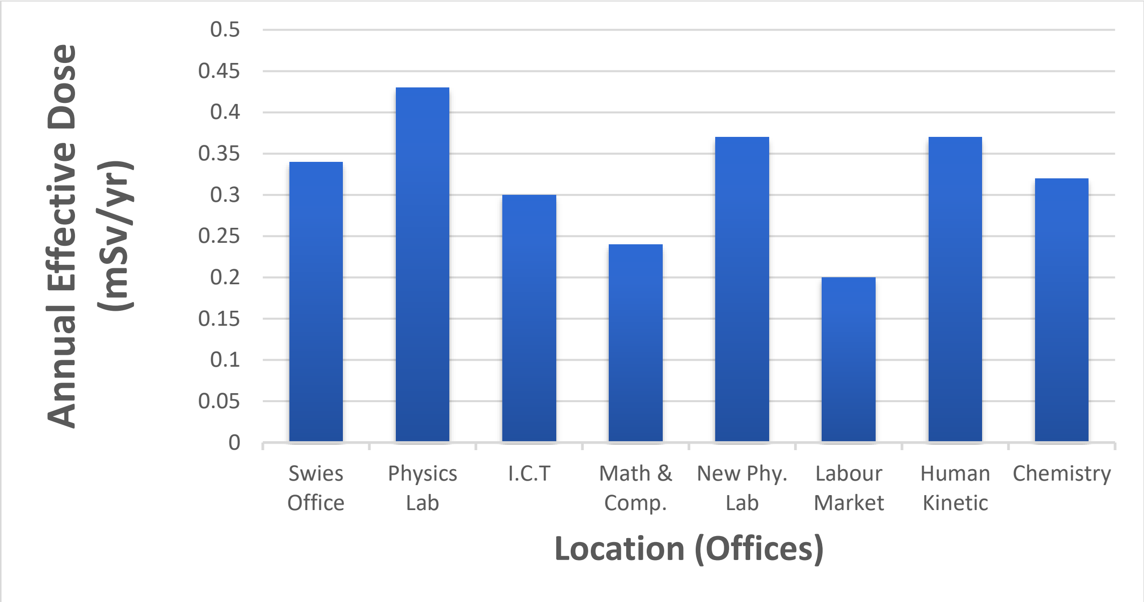

Figure 1: The Annual Effective Dose against the types of locations within Benue State University First Campus Makurdi

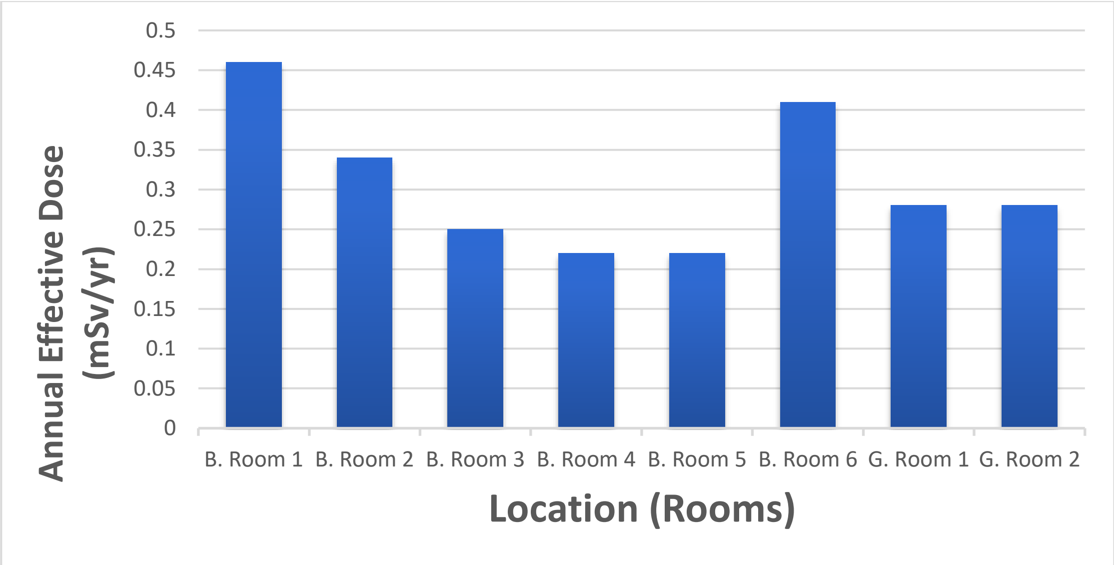

Figure 2: The AEDR against the types of locations within BSU Hostel's Makurdi

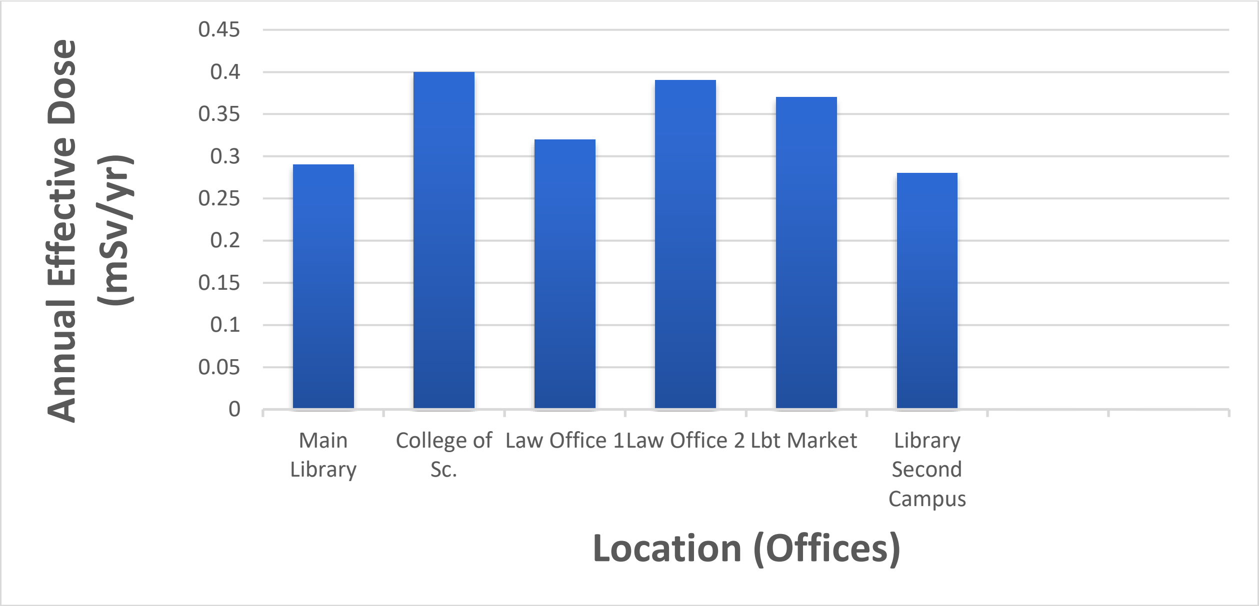

Figure 3: The Annual Effective Dose against the types of locations within Benue State University Second Campus Makurdi

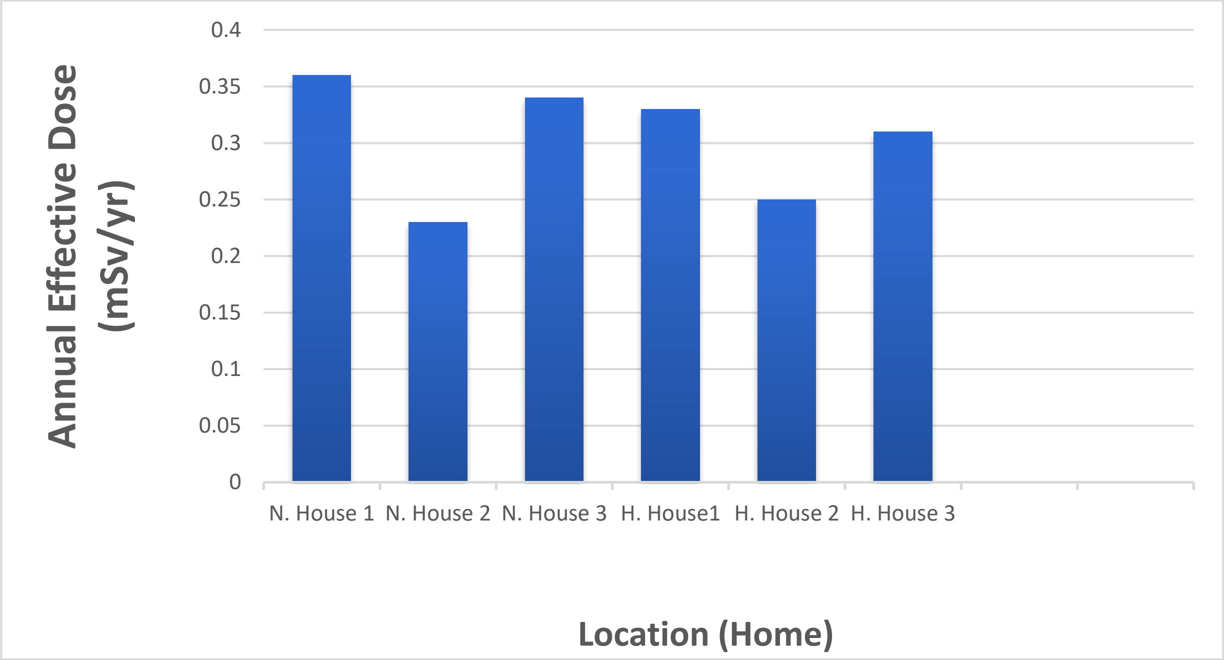

Figure 4: The Annual Effective Dose against the types of locations within some selected places in Makurdi

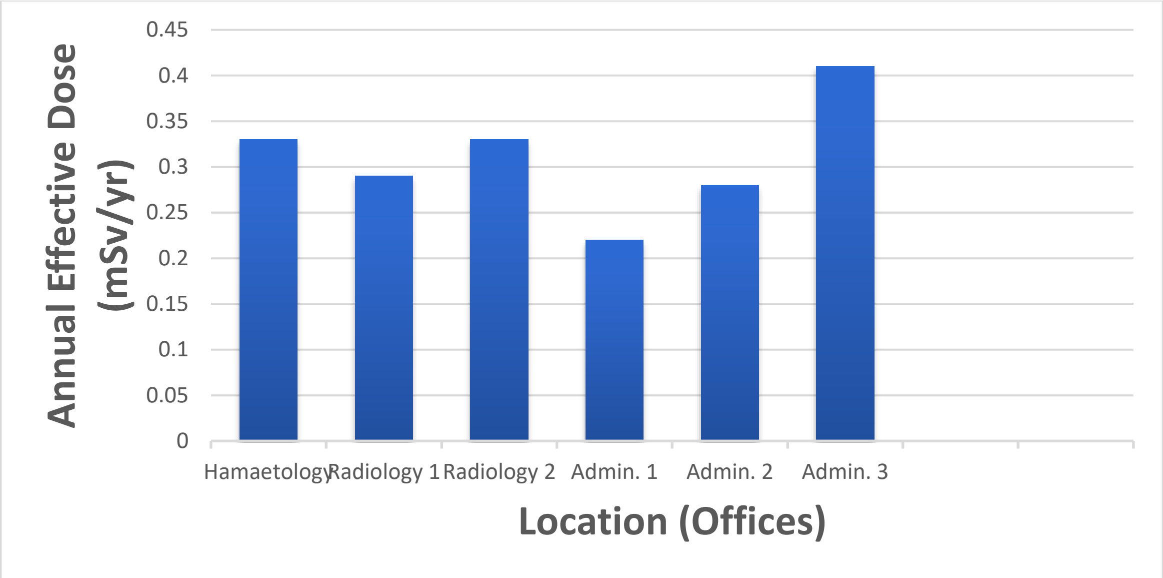

Figure 5: The AEDR against the types of locations within Benue University Teaching Hospital Makurdi

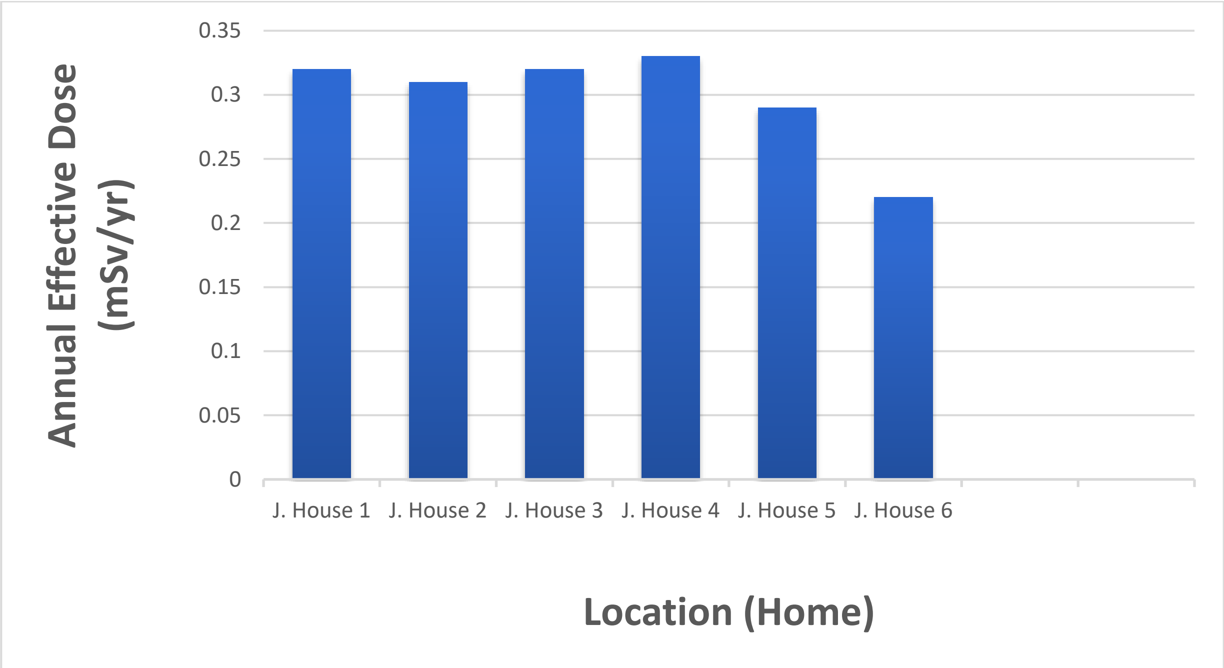

Figure 6: The AEDR against the types of locations within some selected places in Makurdi

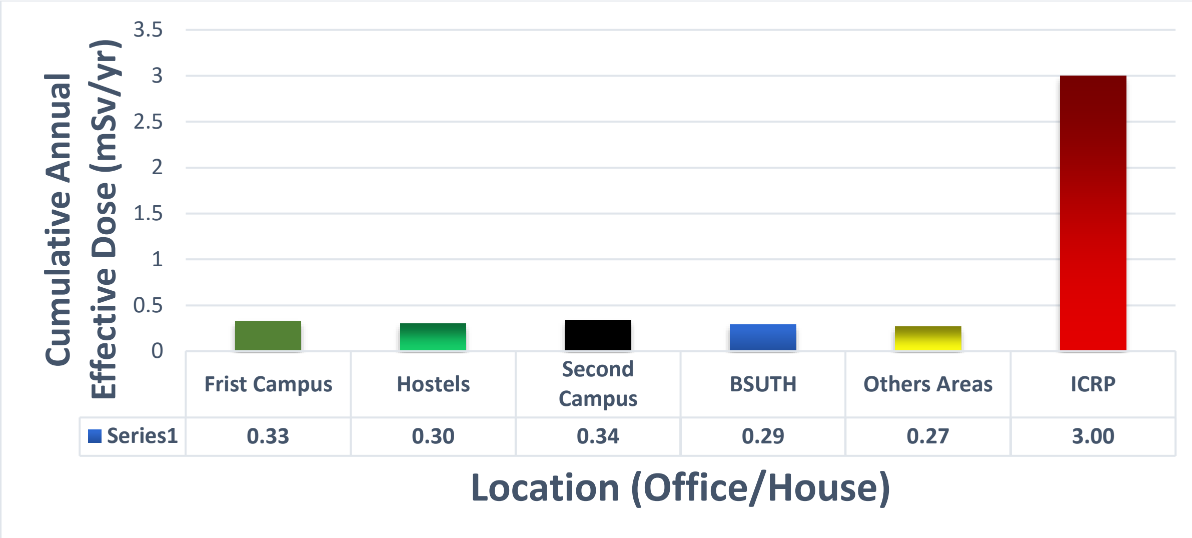

Figure 7: Cumulative AEDR from different locations compare to the International Commission of Radiation Protection.

Discussion

The amount of Radon concentration obtained from the different locations and offices within Benue State University were all within the ‘permissible reference level’ recommended by WHO. The mean value of radon obtained in this study location is like the average indoor radon level estimated worldwide (about 48.1 Bq/m³.) (WHO, 2007). In Table 1, the result carried out for different locations At BSU's first campus, shows that the highest average indoor radon mean concentration was 17.02 +2.22 Bq/m^3 with the highest annual effective dose of 0.43 mSv/yr which is from the Physics Lab. At BSU Hostels, presented in Table 2, it was found that the highest average indoor radon mean concentration is 18.50 + 3.70 Bq/m^3 with the highest annual effective dose of 0.46 mSv/yr from the boys' hostel bathroom because of poor ventilation. For Table 3, At BSU Campus, the highest average indoor radon mean concentration was found to be 15.73 + 0.18 Bq/m^3 with the highest annual effective dose of 0.40 mSv/yr from the College of Health Sciences Hostel. Also, for Table 4, at BSUTH, the highest average indoor radon mean concentration was found to be 16.24 + 1.76 Bq/m^3 with the highest annual effective dose of 0.41 mSv/yr from the administrative block (some cracks on the wall and poor ventilation).

This research also considered geographical demography by considering locations with a higher plain compared to Benue State demography. From the results carried out At Tilley Gyado College North Bank, Cocoa Cola, High-Level Makurdi, there are mostly Burnt brick houses, cement blocks, zinc roofing, aluminium sheet houses and mostly painted and good ventilation, the highest average indoor radon mean concentration is 14.43 + 0.37 Bq/m^3 with the highest annual effective dose as 0.36 mSv/yr from house 1 North Bank (not properly ventilated and cracks on the wall with poor ventilation).

The above results show that the indoor Radon mean concentration in these sample offices could be because of the nature of the building material (cemented, tiled, painted, zinc roofing, and aluminium sheet houses and these are old houses), poor ventilation and cracks on the walls. This could be following the fact that Radon concentration depends on meteorological and geological conditions, construction materials and ventilation (Orlando et al., 2004). It was established by Afolabi et al. (2015) that Radon exposure in homes and offices may arise from surfaces of rock formations and certain building materials; also, the greatest risk of radon exposure is from tight, insufficiently ventilated buildings and buildings that have cracks that let in soil air from the ground into basement and dwelling rooms.

Considering the result between North Bank demography which is of higher plain than BSU Campus which is of lower demography, the average indoor radon mean concentration is higher in BSU than in North Bank which shows the fact that, radon reduces in concentration with elevation in buildings and high plains and increases with decent to the lower plain or the ground floor of the building. This is consistent with literature which reveals that the higher the elevation in a building, the lower the radon level and that higher concentrations of radon are present in basement and ground floor buildings (Shirav & Vulkan, 1997). The detrimental effect of radon exposure obtained from these study areas is seen to be insignificant as compared acceptable tolerant limit of 200Bq/m^3 and 600Bq/ m^3 as recommended by ICRP for residential buildings. Although Darby et al. (2005), show that no level of radon is safe. The result revealed that the radon level obtained from these sampled offices ranges from 7.77 Bq/m^3 to 18.05 Bq/m^3, which all fall within the permissible level as recommended by the World Health Organization (WHO).

CONCLUSION

The average indoor radon concentration in various selected areas within Makurdi Metropolis was calculated to be 12.23 ± 1.68 Bq/m3, resulting in an overall annual effective dose of 0.31 mSv/yr, which falls below the international recommended limit set by WHO in 2007. Based on these measurements, the areas can generally be considered safe in terms of potential health hazards associated with radon exposure. The estimated lung cancer risk in these selected places in Makurdi was found to be insignificant when compared to the EPA's recommended estimated risk range of 3-10 mSv/yr, further indicating that these locations may be deemed safe concerning the risk attributed to radon exposure.

REFERENCES

Afolabi, O. T., Esan, D. T., Banjoko, B., Fajewonyomi, B. A., Tobih, J. E., & Olubodun, B. B. (2015). Radon level in a Nigerian University Campus. *BMC Research Notes*, *8*(1), 677. https://doi.org/10.1186/s13104-015-1447-7

Appleton, J. D. (2007). Radon: sources, health risks and hazard mapping. *A Journal of the Human Environment*, *36*(1), 85–90. https://doi.org/https://doi.org/10.1579/0044-7447(2007)36[85:rshrah]2.0.co;2

Celen, Y. Y., Oncul, S., Narin, B., & Gunay, O. (2023). Measuring radon concentration and investigation of it's effects on lung cancer. *Journal of Radiation Research and Applied Sciences*, *16*(4), 100716. https://doi.org/10.1016/j.jrras.2023.100716

Cember, H., & Thomas, J. E. (2000). Introduction to Health Physics: Fourth Edition. *Medical Physics*, *35*(12), 5959–5959. https://doi.org/10.1118/1.3021454

CHEN, B., YUAN, T. W., WANG, A. Q., ZHANG, H., FANG, L. J., WU, Q. Q., ZHANG, H. B., TAO, S. S., & TIAN, H. L. (2018). Exposure to Radon and Kidney Cancer: A Systematic Review and Meta-analysis of Observational Epidemiological Studies. *Biomedical and Environmental Sciences*, *31*(11), 805–815. https://doi.org/10.3967/bes2018.108

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., … Doll, R. (2005). Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. *BMJ*, *330*(7485), 223. https://doi.org/10.1136/bmj.38308.477650.63

Hahn, E. J., Gokun, Y., Andrews, W. M., Overfield, B. L., Robertson, H., Wiggins, A., & Rayens, M. K. (2015). Radon potential, geologic formations, and lung cancer risk. *Preventive Medicine Reports*, *2*, 342–346. https://doi.org/10.1016/j.pmedr.2015.04.009

Hopke, P. K., Borak, T. B., Doull, J., Cleaver, J. E., Eckerman, K. F., Gundersen, L. C. S., Harley, N. H., Hess, C. T., Kinner, N. E., Kopecky, K. J., McKone, T. E., Sextro, R. G., & Simon, S. L. (2000). Health Risks Due to Radon in Drinking Water. *Environmental Science & Technology*, *34*(6), 921–926. https://doi.org/10.1021/es9904134

Kendall, G. M., & Smith, T. J. (2002). Doses to organs and tissues from radon and its decay products. *Journal of Radiological Protection*, *22*(4), 389–406. https://doi.org/10.1088/0952-4746/22/4/304

Orlando, P., Trenta, R., Bruno, M., Orlando, C., Ratti, A., Ferrari, S., & Piardi, S. (2004). A study about remedial measures to reduce 222Rn concentration in an experimental building. *Journal of Environmental Radioactivity*, *73*(3), 257–266. https://doi.org/10.1016/j.jenvrad.2003.09.003

Shirav, M., & Vulkan, U. (1997). Mapping radon-prone areas - a geophysical approach. *Environmental Geology*, *31*(3–4), 167–173. https://doi.org/10.1007/s002540050176

UNSCEAR. (2000). Sources and Effects of Ionizing Radiation Volume I: source. In *United Nations Scientific Committe on the Effects of Atomic Radiation: Vol. I.*

US EPA. (2014). *EPA facts about radon*. *July*. https://semspub.epa.gov/work/HQ/176336.pdf

Wang, Z. (2002). Natural radiation environment in China. *International Congress Series*, *1225*, 39–46. https://doi.org/10.1016/S0531-5131(01)00548-9

WHO. (2007). *Indoor Radon a Public Health Perspective*. 110. https://www.ncbi.nlm.nih.gov/books/n/whoradon/pdf/