Original Research Article

Age-dependent Radiological Risk Assessment of Radon (^{222}Rn) in Samples of Commercial Bottled Water from Benin City, Nigeria

ABSTRACT

Radon inhalation as well as ingestion through the use of water has a high potential of causing serious harm to sensitive cells and organs of the body when absorbed into the bloodstream. Therefore, this study aimedto assess the radiological health damage caused by radon in drinking bottled water available in Benin City, Edo State, Nigeria. Radon concentration was measured using a RAD7 electronic radon detector. The mean activity concentration radon is 137.18 ± 0.25 mBq/L. This mean value is slightly higher than 0.1 Bq/L recommended by the Standard Organisation of Nigeria but lower than the maximum contaminant level (MCL) of 11.1 Bq/L set by the United States Environmental Protection Agencyand 100 Bq/L set by the World Health Organisation (WHO) for consumption of radon in drinking water.The mean total annual effective doseis1.07±1.91(μSv/y) for infants, 0.61±1.09(μSv/y) for children, and 0.70±1.24 (μSv/y) for adults. The computed annual effective dose to the public by inhalation and ingestion radon through the use of bottled water in the study areas are lower than the 0.1 mSv/y limit recommended by WHO. The estimated average for the age group excess lifetime cancer risk are3.21 ± 5.71, 1.836 ± 3.26, 2.086 ± 3.71 ($\times 10^{-6}$) for infants, children and adults respectively. These values are below the world average permissible levels. Hence, consumption of the water examined poses no serious health risk to consumers.

Keywords: Bottled water, radon (^{222}Rn), Benin City,cancer risk, effective dose, RAD7 detector

UNDER PEER REVIEW

INTRODUCTION

Water isincredibly an important aspect of lives(Jain and Singh 2019).Water makes up about 60% of body weight in men and 55% in womenand for infants it is about 70%–80% (Jain and Singh 2019).Unrefined water includes a range of pollutants, including biological, chemical, and radioactive contaminants (Oni et al. 2021).Mostpeople dependprofoundly on groundwater sources as a result of population growth, the contamination of streams, and the inadequacy of the government's potable water supply, numerous individuals have resorted to consuming treated water, such as bottled water and sachet water. In Nigeria, sachet water and bottled water have become increasingly embraced as a substitute for the inadequate safe drinking water from the government's pipe-borne water system.Bottled drinking water is water derivedfrom any source of potable water (well, bore well, groundwater) which may be subjected to different treatment processessuch as decantation, filtration, aeration, reverse osmosis, ozonation, ultraviolet treatment, silverionization, other similar methods(Jain and Singh 2019)

Radioactivity is a natural phenomenon and natural sources of radiationare features of the environment. Exposure of human tissues or organs to radiation can induce the death ofcells on a scale that can be extensive enough to impair the function of the exposedtissue or organ(IAEA 2014).Radon is a radioactive, colourless,odourless, and tasteless gas that is formed through the breakdown of uranium in soil and rocks(Opoku-Ntim et al. 2019). Radon is acknowledged as a cancer-causing substance. It is the most dangerous radioisotope to human health of all the radioactive elements that contribute to natural background radiation (NRC 1999).The most abundant form of radon is Rn-222, with a half-life of 3.82 days. Rn-222 is a decay product of radium (Ra-226), and a member of the U-238 decay chain (the most common isotope of

UNDER PEER REVIEW

uranium). It occurs at low levels in mostrocks, soil, water body, plants, and animals (Kamba and Okunade 2016).

Many uses of waterrelease radon into the indoor airbecause radon is easily released by agitation in water.This contributes to the total indoor airborneradon concentrations. Ingestion of radon in water is also thought to pose a directhealth risk through irradiation of sensitive cells in the gastrointestinal tract and inother organs once it is absorbed into the bloodstream. Thus, radon in drinkingwater could potentially produce adverse health effects in addition to lung cancer (NRC 1999).Once radon has entered the blood,through either the stomach or the small intestine, it is distributed among theorgans according to the blood flow to them and the relative solubility of radon inthe organs and in blood. Radon dissolved in blood that enters the lung willequilibrate with air in the gas-exchange region and be removed from the body (NRC 1999).

Radon levels and radiological safety of bottled and sachet water have been investigated by several researchers in Nigeria and other countries of the world. The sachet water consumed in Damaturu, Yobe State, Nigeria, as reported by Abba and Umaru (2020), has some level of radiological implications due to radon contamination.Yong et al.(2020) measured the radon concentrations of 15 differentbrands of commercial bottled drinking water producedin China and assessed the impacts on humanhealth from commercial bottled water. The relationship between different mineral content andradon concentration in drinking mineral-water was alsoexplored.Despite bottled mineral water not posing a significant health risk to the public, study results showed radon levels were strongly correlated with its total dissolved solids and calcium concentration.Recently, with the RAD7 Radon monitoring system, Al Mahmud et al. (2023) measured radon levels in commercial bottled water and deep well water samples, finding results that were significantly lower than USEPA and WHO recommendations.Oni et

UNDER PEER REVIEW

al.(2021)determined the radon concentrations present in seventeen brands of sachet and bottled water packaged in Ile-Ife, South West Nigeria. Kadhim et al.(2021) assessed the radon concentrations from samples of bottled water available in the Iraqi markets.A study conducted by Bayayaet al. (2020) measured the levels of activity in radon-222 in water samples collected from different sachet water companies in Dutsin-Ma local government area of Katsina State, Nigeria.According to the authors, water consumption does not pose significant health risks from a radiological standpoint.In spite of this, radiation levels in the environment need to be continuously monitored.

Thorough assessments and monitoring of drinking water quality, as well as concentrations of radon activity, are paramount to public health and safety. However, no study of this sort has been carried out in Edo State.Benin City which is the commercial hub of Edo State was chosen for this study. The study, therefore, aimed to determine the activity concentrations of radon (^{222}Rn) in bottled water in Benin City, Nigeria, and assess the health hazards associated with ingestion and inhalation of radon.

MATERIALS AND METHODS

Study area

Benin City is the capital of Edo State, Nigeria and is located in the south-south geopolitical zone of Nigeria. The city has an area of 1, 204 km^2 and a population of approximately 1.84 million people (2022 population projection). The area is bounded is by longitudes 4°36′– 4°39′E and latitudes 8°27′–8°30′ *N*and area of about 500 square kilometres. Benin City is located within a tropical equatorial zone where there are two distinct seasons, one wet season from April to October and one dry season from November to March (Erah et al. 2002).

Sampling and preparation

UNDER PEER REVIEW

Ten brands of bottled water produced and sold or vended in Benin City were examined. Three bottles (75 cl each) of each of the brands were purchased from diverse stores, markets, and street hawkers in Benin city. A 1.5 L bottle, previously rinsed and washed with distilled waterwas used for the collection of water samples.In the process of putting the water into the collection bottles,water bubbling was carefully prevented to stop dissolved radon from escaping. The experimental procedures used in this investigation were those published by Osahon *et al.*(2018). The prepared samples were sealed and taken to the Ladoke Akintola University's Radiation and Health Physics Laboratory, Department of Physics, for radon analysis.

Radon measurementusing RAD7

RAD7 (Figure 1) is a radon detector that is well-calibrated, quick, and accurate. The electronic detector employs the alpha spectrometry method with a bubbling kit. Alpha spectrometry method using RAD7 has widely been used by (Abba and Umaru 2020; Al Mahmud *et al.* 2023; Kadhim *et al.* 2021; Oni *et al.* 2021; Osahon *et al.* 2018).It can precisely assess the radon levels in a water sample in 20 minutes. The time required is quite short when compared to the radon half-life of 3.8 days, and as a result, the RAD7 detector is a good choice for measuring radon in water(DURRIDGE 2020; Oni *et al*. 2014).

UNDER PEER REVIEW

Figure1: Setup of RAD-7 for radon measurement in water(DURRIDGE, 2020)

Having obtained the values for the radon activityconcentrations of each of the naturalradionuclides in the bottled water, a calculation of the yearly effective dosage of radon from ingestion ()based on equation (1) was made(UNSCEAR 2000; Oni *et al.* 2016; Yong *et al.* 2020; Kadhim *et al.* 2021; and Sukanya *et al.* 2021)

$$AED_{Ing} = \mathrm{C_{RnW}} \times C_f \times A_{\mathrm{WI}} \quad (1)$$

Where C_{RnW} is the activity concentration of ^{222}Rn in (Bq/L), $AI_{\mathrm{W}}$is the yearly consumption of drinking water (L/y), C_{f} is the age-dependent ingested dose conversion factor for ^{222}Rn.

As per UNSCEAR (2000), the mean effective doses of radon due to inhalation (AED_{inh}) in drinking water samples were calculated (Yong *et al.* 2020; Opoku-Ntim *et al.* 2019):

$$AED_{Inh}(\mu Sv/y) = \mathrm{C}_{RnW} \times R_{a.W} \times \mathrm{F} \times \mathrm{O} \times D_{CF} \quad (2)$$

where $AED_{Inh}$is the effective dose for inhalation, C_{RnW} is the radon concentration in water, $R_{a.W}$ is the ratio of radon in air to radon in tap water (1×10^{-4}), F is the equilibrium factor between radon and its decay products (0.4), O is the average indoor occupancy time per person (7000 h/y)

UNDER PEER REVIEW

and D_{CF} is the Dose Conversion Factor for radon exposure. Infants, children, and adults consume approximately 260, 350, and 730 litresof water per year, respectively (Opoku-Ntim *et al.* 2019; Orosun*et al.* 2022) and the ingested dose conversion factor per age group are 2.3×10^{-8}, 5.9×10^{-9}, and 3.5×10^{-9} (Sv/Bq) respectively (UNSCEAR, 2000; Yong *et al.* 2020; Kadhim *et al.* 2021; Sukanya *et al.* 2021).

The total Annual Effective Dose () as a result of ingestion and inhalation of radon through the use of the bottled water in the study area was obtained using equation (3)

$$AED_{Tot} = AED_{Ing} + AED_{Inh} \quad (3)$$

The lifetime cancer risk associated with radon concentrations in drinking water was calculated using equation (4) (Kadhim *et al.* 2021; Dankawu *et al.* 2022).

$$\text{ELCR} = \text{Annual effective dose} \times \text{Average lifespan} \times \text{Risk coefficient} \quad (4)$$

where, the nominal risk coefficient for the whole population is based on the International Commission on Radiological Protection public (ICRP 2007). In Nigeria, the average life expectancy at birth is 54.5 years, according to the WHO (2015) report.

RESULTS AND DISCUSSION

Radon concentration

The radon activity concentrations, as presented in Table 1, are from a minimum value of 20.83 ± 0.18mBq/L in BTW 2 to a maximum of 340.28 ± 0.33 mBq/L in BTW 1 with a mean of 137.18± 0.25 mBq/L. The radon concentration value of BTW 8 is slightly closer to the maximum

Table 1: Radon concentrations (mBq/L) in bottled water in Benin City.

Sample ID	Radon Concentrations (mBq/L)
BTW 1	340.28 ± 0.33

UNDER PEER REVIEW

BTW 2	20.83 ± 0.18
BTW 3	21.10 ± 0.19
BTW 4	20.83 ± 0.19
BTW 5	20.94 ± 0.19
BTW 6	41.65 ± 0.20
BTW 7	41.65 ± 0.20
BTW 8	337.52 ± 0.34
BTW 9	232.01 ± 0.30
BTW 10	294.95 ± 0.32
Minimum	20.83 ± 0.18
Maximum	340.28 ± 0.33
MEAN	137.18 ± 0.25

concentration recorded.There is a slight increase in the mean radon activity concentrations in this study over the 0.1 Bq/L recommended by the Standard Organisation of Nigeria (SON 2015) for human consumption of ^{222}Rn concentrations in drinking water, but it is significantly below the maximum contaminant level (MCL) of 11.1 Bq/L recommended by the USEPA (USEPA 1999) and 100 Bq/L suggested by the WHO (WHO 2011).

Table 2: Comparison of range/mean of radon activity concentrations in other part of the world with this study.

Location	Water type	^{222}Rn Conc. (mBq/L)	References
Turkey	Bottled water	30.6–57.6 /43.1	Seid et al. 2020
Dhaka/Bangladesh	Bottle water	105–1300/590	Al Mahmud et al. 2023
Urumqi/China	Bottled water	13.3–300/21.6	Yong et al. 2020
Ile-Ife	Bottled water	0–9449.3/2442.8	Oni et al. 2021

UNDER PEER REVIEW

Iraq	Bottle water	28.4–283/104.14	Kadhim et al. 2021
Damaturu/Yobe	Sachet water	4420–20210	Abba and Umaru 2020
Dutsin-Ma/Katsina	Sachet water	11690–13040/12037	Baraya et al. 2020
Benin City	Bottled water	20.83–340.28/137.18	This study

The mean radon concentrations obtained in this study are slightly higher than those obtained by Yong *et al.*(2020) in China, Seid *et al*. (2020) in Turkey, Kadhim *et al*. (2021) in Iraq and Baraya *et al.*(2020) in Katsina, Nigeria, as shown in Table 2. Osahon et al. (2018), Al Mahmud et al. (2023) and Oni et al. (2021) reported radon mean concentrations greater than the obtained value in this study.The explanation for this low amount of radon in bottled water can be linked to the processing method employed by the bottled water factories, because radon gas is easily emitted when groundwater is agitated. In addition, the geological formation, soil porosity, meteorological parameters of the study area can also be a contributory factor(Opoku-Ntim et al. 2019).

Annual Mean Effective Dose of Radon

The results of the analysis of bottled water sold in Benin City indicate that the AED have minimum, maximum and mean values of 0.11±0.95, 1.80±1.80 and 0.73±1.29 (μSv/y) for infants; 0.04±0.35, 0.66±0.66 and 0.27±0.48 (μSv/y) for children; 0.05±0.46, 0.87±0.87 and 0.35±0.62 (μSv/y) for adults respectively. The inhalation for all ages has minimum, maximum and mean values of 0.05±0.45, 0.86±0.86 and 0.35±0.61 (μSv/y). These findings are summarized in Table 3 and

Table 3: Annual effective dose of radon (μSv/y) in bottled water in Benin City.

Sample ID	Ingestion (μSv/y)	Inhalation	Total AED (μSv/y)

UNDER PEER REVIEW

	Infant	Children	Adults	(µSv/y)	Infant	Children	Adults
BTW 1	1.80±1.75	0.66±0.64	0.87±0.84	0.86±0.83	2.66±2.58	1.52±1.47	1.73±1.67
BTW 2	0.11±0.95	0.04±0.35	0.05±0.46	0.05±0.45	0.16±1.41	0.09±0.80	0.11±0.91
BTW 3	0.11±1.01	0.04±0.37	0.05±0.49	0.05±0.48	0.16±1.48	0.09±0.85	0.11±0.96
BTW 4	0.11±1.01	0.04±0.37	0.05±0.49	0.05±0.48	0.16±1.48	0.09±0.85	0.11±0.96
BTW 5	0.11±1.01	0.04±0.37	0.05±0.49	0.05±0.48	0.16±1.48	0.09±0.85	0.11±0.96
BTW 6	0.22±1.06	0.08±0.39	0.11±0.51	0.11±0.50	0.33±1.56	0.19±0.89	0.21±1.02
BTW 7	0.22±1.06	0.08±0.39	0.11±0.51	0.11±0.50	0.33±1.56	0.19±0.89	0.21±1.02
BTW 8	1.79±1.80	0.66±0.66	0.86±0.87	0.85±0.86	2.64±2.66	1.51±1.52	1.72±1.73
BTW 9	1.23±1.59	0.45±0.58	0.59±0.77	0.59±0.76	1.81±2.34	1.04±1.34	1.18±1.52
BTW 10	1.56±1.69	0.57±0.62	0.75±0.82	0.74±0.81	2.30±2.50	1.32±1.43	1.50±1.62
Minimum	0.11±0.95	0.04±0.35	0.05±0.46	0.05±0.45	0.16±1.41	0.09±0.80	0.11±0.91
Maximum	1.80±1.80	0.66±0.66	0.87±0.87	0.86±0.86	2.66±2.66	1.52±1.52	1.73±1.73
MEAN	0.73±1.29	0.27±0.48	0.35±0.62	0.35±0.61	1.07±1.91	0.61±1.09	0.70±1.24

PEER REVIEW

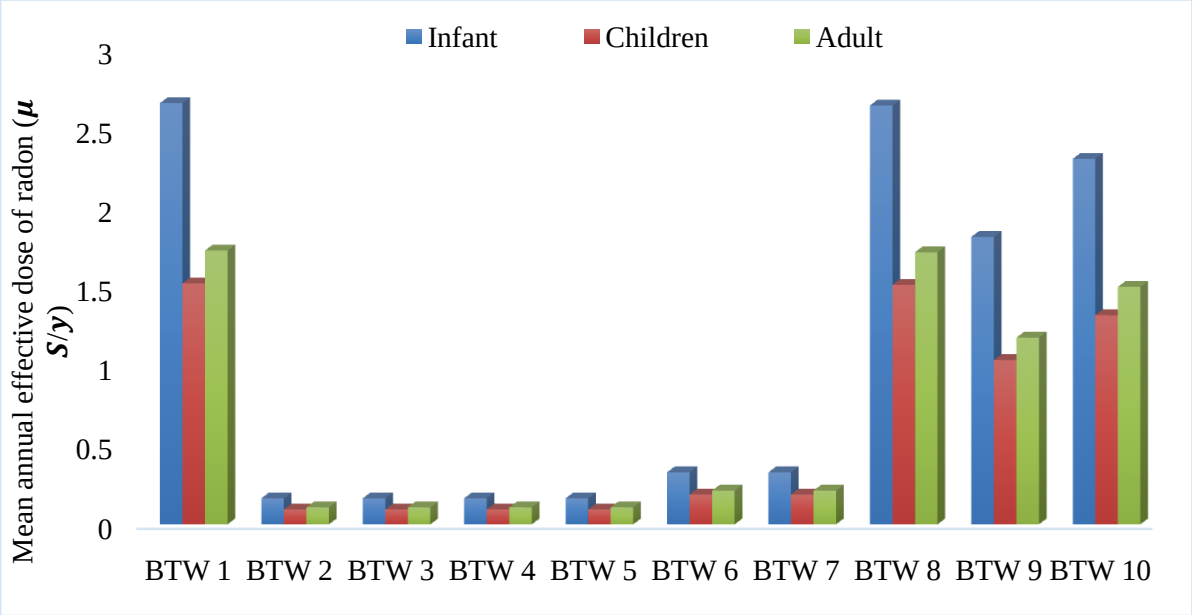

Fig. 2: Total annual effective dose of radon (µSv/y) of bottled water inBenin City, Edo State.

depicted in Figure2. The mean total AED are 1.07±1.91, 0.61±1.09 and 0.70±1.24 (μSv/y)for infants, children and adults respectively. The infants recorded the highest value contributing 45% of the mean total AED, whereas the children and adults contributed 29% and 26% respectively. All the sampled bottled waters are below 0.1 mSv/y (WHO 2009).

The infants age category recorded the highest radiation dose contributing 45% of the mean total AED. This implies that infants are the most susceptible to radiation exposure from radon intake. The probable cause can be connected to the high quantity of radon that they absorb per kilogram of body mass as a result of low organ mass and rapidly dividing cells (Sukanya *et al.* 2021), despite the lower volume of water intake compared to children and adults. Adults are the second most vulnerable group to radon exposure, probably due to increased water use.However, there is just a little variation between adult and children category dosages, which is consistent with (Sukanya *et al.* 2021).The computed annual effective dose to the general population by inhalation and ingestion in the study areas are less than the 0.1mSv/y level recommended by WHO (2009) and 1 mSv/y ICRP, (2000). Comparatively,this study's annual effective dose (Sv/y) of radon in consistent with the findings of Seid *et al.*(2020) and Yong *et al.*(2020) and lower than 0.023-0.148 mSv for adults and 0.046-0.295 mSv for children reported by Abba and Umaru (2020) and 25.56 ± 2.69, 19.48 ± 2.05 and 42.56 ± 5.58Sv/y for adults, children, and infants respectively reported by Osahon *et al.*(2018).

Table 4: Excess Lifetime Cancer Risk from consumption of bottled water inBenin City, Edo State.

UNDER PEER REVIEW

Sample ID	ELCR ($\times 10^{-3}$)		
	Infant	Children	Adults
BTW 1	7.913 ± 7.73	4.526 ± 4.41	5.141 ± 5.01
BTW 2	0.492 ± 4.23	0.282 ± 2.40	0.321 ± 2.73
BTW 3	0.492 ± 4.44	0.282 ± 2.55	0.321 ± 2.88
BTW 4	0.492 ± 4.44	0.282 ± 2.55	0.321 ± 2.88
BTW 5	0.492 ± 4.44	0.282 ± 2.55	0.321 ± 2.88
BTW 6	0.983 ± 4.68	0.564 ± 2.67	0.638 ± 3.06
BTW 7	0.983 ± 4.68	0.564 ± 2.67	0.638 ± 3.06
BTW 8	7.913 ± 7.97	4.526 ± 4.56	5.141 ± 5.19
BTW 9	5.431 ± 7.01	3.105 ± 4.02	3.528 ± 4.56
BTW 10	6.906 ± 7.49	3.951 ± 4.29	4.487 ± 4.86
Minimum	0.492 ± 4.23	0.282 ± 2.40	0.321 ± 2.73
Maximum	7.913 ± 7.97	4.526 ± 4.56	5.141 ± 5.19
MEAN	3.21 ± 5.71	1.836 ± 3.26	2.086 ± 3.71

Evaluation of Excess Lifetime Cancer Risk

The results of the excess lifetime cancer risk presented in Table 4 indicate that the mean value is 3.21 ± 5.71, 1.836 ± 3.26, 2.086 ± 3.71 ($\times 10^{-6}$) for infants, children and adults respectively. The infants recorded higher value than adults and children. Internal radon exposure is extremely dangerous and can result in respiratory disorders such as asthma (Avwiri et al. 2014). However, the result obtained in the study, for all age categories, were below the world average permissible level of 0.2×10^{-3}(UNSCEAR 2000). Hence, consumption of the water examined poses no health threat to anyone that takes it.

CONCLUSION

UNDER PEER REVIEW

This study examined the radiological evaluation of ^{222}Rn in several random samples of bottled water available in Benin City.The results demonstrate that the mean radon concentration is somewhat greater than the 0.1 Bq/L suggested by the Standard Organization of Nigeria (SON 2015) but still relatively low when compared to the standard levels recommended by the USEPA (1999), UNSCEAR (2000), and WHO (2011). The computed annual effective dose to the general public via inhalation and ingestion in the study areas were lower than the 0.1 mSv/y limit recommended by (WHO 2009) and 1 mSv/y (ICRP 2000). The infants are mostly irradiated by consumption of these bottled waters. The age group evaluation of the lifetime cancer risk, were below the set limit of0.2×10^{-3}(UNSCEAR 2000). By implication, consumption of the water examined poses no significant health hazard to consumers. Nevertheless, the water factories should improve on the purification process by employing a more effective radon reduction methods to ensure radon free water for consumption.Subsequently, thefindings of this study might be used to establish a baseline for a radiological implication of radon in water in Edo State.

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UNDER PEER REVIEW

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UNDER PEER REVIEW

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UNDER PEER REVIEW