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Assessment of occupational exposure to radon-222 in water treatment and production plants in Ogbomoso, South-western, Nigeria

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► ***Original article***

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ABSTRACT

Background: The transfer of dissolved radionuclide in water into the indoor air is one of the major pathways for radon-222 (^{222}Rn). In water treatment and production plants (WTPPs), there is a risk that radon degasses from the water and enters into the indoor air. Hence, this study assessed different WTPPs to determine the amount of ^{222}Rn workers are exposed to as a result of their occupation. ***Materials and Methods***: An Electret Passive Environmental Radon Monitor (E-PERM$^{®}$) device was used to investigate the indoor radon levels in the processing, packaging, and storage rooms of five (5) well-known and active WTPPs in Ogbomoso, Nigeria, and descriptive statistics was used for the analysis of data obtained. ***Results***: The radon concentration obtained varies between 44 - 149 Bq/m^3 with an average of 69.28 ± 20.06 Bq/m^3 in the processing rooms, 27 – 44 Bq/m^3 with an average of 36.02 ±4.05 Bq/m^3 in the packaging rooms and 34 – 144 Bq/m^3 with an average of 71.15 ± 42.81 Bq/m^3 in the storage rooms. The average annual effective dose obtained for each of the WTPPs varies between 1.00 mSvy^{-1} and 2.00 mSvy^{-1}. ***Conclusion***: The results showed that all the investigated WTPPs had high radon concentration and annual effective dose when compared with the action level proposed by local and international organizations. Hence, the workers are at risk to ^{222}Rn during water treatment and production processes.

INTRODUCTION

Water, one of the three most important natural resources alongside air and soil, is an essential commodity of life that human being cannot do without. Hence, its necessity cannot be taken for granted. It serves as a solvent that promotes chemical activities, transportation medium for nutrients, hormones, enzymes, minerals, nitrogenous waste, respiration gases and several other important functions (1, 2). To be potable for use without causing damage to human health (3), water meant for domestic purposes must be free of harmful concentrations of chemicals, pathogenic microorganisms, and radionuclides. Of concern is the presence of radionuclides in water arising from trace amounts of terrestrial radionuclides from the decay series of uranium-238 (^{238}U), thorium-232 (^{232}Th), and the singly occurring potassium-40 (^{40}K), most of which are dissolved solids from rocks, soils and mineral deposits (4). The presence of radionuclides in water can cause internal exposure in humans which results from the decay of radionuclides taken into the body through ingestion and inhalation (5). These radionuclides are then distributed within the sensitive organs of the human body according to the metabolism of the element involved (6, 7). Of radiological concern to human health is the exposure to Radon-222 (^{222}Rn), a noble gas formed from Radium-226 (^{226}Ra), a decay product of ^{238}U. Radon, which has a half-life of 3.8 days, emanates from rocks and soils, tends to concentrate in enclosed spaces like underground mines or buildings. It is a major contributor to the ionizing radiation dose received by the general population (4). The knowledge of the sources and transport mechanisms of radon gas can be traced back to the 1950s, when high concentrations of radon were observed in domestic and drinking water from drilled wells. The initial concern about radon in water focused on the effects of ingestion of the water. However, it was later discovered that the primary health risk of radon in water was from the inhalation of radon gas released indoors (8).

Water treatment and production plants (WTPPs) involve the removal of contaminants from raw water to produce water that is pure and potable for human consumption without any short- or long-term risk of any adverse health effects. Hence, the business of WTPPs has been on the increase globally owing to the increase in world population (9, 10), and of concern is the presence of ^{222}Rn in water (11). Many methods of

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water treatment are available in the literature and have been applied for the removal of chemicals and pathogenic microorganisms. However, the removal of ^{222}Rn from water can only be achieved through aeration, granular activated charcoal (GAC) and storage (12). These treatment methods are limited by the technical and financial capability of the owner of the WTPP and often have an impact on the radon concentration in water as it influences its transfer into the air (13, 14). Irrespective of the method selected, ^{222}Rn, one of the highest water-soluble noble gases, may have higher concentrations in water from underground sources. As the water gets aerated or backwashed, elevated concentrations of radon gas may be released and get diffused within the enclosures of the WTTPs (15). The diffused gas mixed with radon gas present in the air from other sources, and the concentration may reach a level that may present a radiological risk to the workers when inhaled (3), a practice that is against one of the Sustainable Development Goals (SDGs) of ensuring availability and sustainable management of water and sanitation for all (16).

There is no doubt that there are extensive studies on radon concentrations in water, both locally and internationally, but little attention has been paid to occupational exposure to ^{222}Rn during water treatment and production processes. Fisher *et al.* observed an average airborne ^{222}Rn concentrations of 3.4 pCi/L (126 Bq/m^3) with a maximum of 133 pCi/L (4921 Bq/m^3) when reporting the occupational exposure of water plant operators to high concentrations of ^{222}Rn (17). A similar study by Kerber *et al.* revealed that the concentration of ^{222}Rn is above the Environmental Protection Agency (EPA) action level of 4.0 pCi/L (148 Bq/m^3) when reporting the occupational exposure to airborne ^{222}Rn in three Minnesota water treatment plants (15). Both studies concluded that since airborne ^{222}Rn concentrations in WTPPs can reach levels considered unsafe, it is important to regularly monitor WTPPs as operators may be at risk when exposed to high airborne ^{222}Rn concentrations during water treatment and production processes. The implication of this is that when radon gas is inhaled as a result of occupational exposure, alpha particles emitted by the deposited short-lived decay products of radon namely polonium -218 (^{218}Po) and polonium-214 (^{214}Po), interact with biological tissue in the lungs leading to deoxyribonucleic acid (DNA) damage (18, 19), thus making the International Agency for Research on Cancer (IARC) to categorize ^{222}Rn as a Class 1 carcinogen.

Due to the increase in population size and the inadequate or unavailability of government pipe-borne water to cater for the increase, the residents of Ogbomoso have embarked on getting water from whatsoever means available. As the city develops, diverse explorations and exploitations of the Earth crust for water (a potential route of radionuclide migration into water) are made by individual, small, medium and cooperate enterprises resulting in the establishment of more WTPPs to meet up with this basic and necessity of life. Many studies on the use of water in Ogbomoso, and its environs revealed the presence of natural radionuclides at elevated concentration (1, 7, 20, 21). However, to the best of our knowledge, scanty attention has been paid to the investigation of occupational exposure to radon gas from WTPPs in the study area in particular and Nigeria in general. Hence, this study examines different popular WTPPs available in Ogbomoso to determine the amount of ^{222}Rn workers are exposed to as a result of their occupation and the implications on human health. The results from this study will serve as a yardstick for future studies on WTPPs in Nigeria.

MATERIALS AND METHODS

Study area

Ogbomoso, is a city in Oyo State, Southwestern Nigeria with geographical coordinates 8^{o}08'N, 4^{o}15'E and elevation 347 m (1138 ft). The city has five Local Government Areas (LGAs), with Ogbomoso North LGA being the city's major economic nerve, with a landmass of 235 km^2. Geologically, the rock formation of the study area is grouped under the gneiss-migmatite complex, mafic-ultra, amphibolite complex, meta-sedimentary assemblages and intrusive suite of granitic rocks, all of which lie within the Precambrian complex rock of Nigeria (22, 23).

Sampling locations

In this study, 5 different WTPPs were considered to determine the level of indoor radon to which the workers are exposed during water production. The locations and geographical coordinates of each WTPPs are presented in table 1. These WTPPs were selected based on their production activities, infrastructure, manpower, popularity, domestic and industrial applications. Figure 1 showed the satellite view of the sampling locations and its immediate environment. In each of the WTPPs the processing (PCG), packaging (PKG) and storage (STG) rooms were selected for the desired point of assessment, as lots of activities such as the automated filling of water into nylon or plastic bottles, sealing, packing and storing take place. These activities are carried out on daily basis in order to meet up with the populace demand and this is a major concern radiologically.

Table 1. Geographical coordinate of the study locations.

Sample Locations	Geographical Coordinate	
	Latitude	Longitude
WTPP$_1$	8°10'55.795"N	4°16'30.235"E
WTPP$_2$	8°11'34.872"N	4°16'30.588"E
WTPP$_3$	8°09'46.533"N	4°15'33.293"E
WTPP$_4$	8°09'36.071"N	4°15'48.862"E
WTPP$_5$	8°09'21.538"N	4°14'59.503"E

Legend: WTPP - water treatment and production plant.

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Figure 1. Satellite view of the sampling locations (Source: Google map).

Instrumentation details

The study employed a passive Electret Ion Chambers (EIC) system for the assessment of radon concentration. The EIC consists of a short-term (ST) electret (an electrically charged piece of Teflon disc) mounted inside a standard (S) chamber (210 mL with an on/off mechanism) and a user-friendly, high-precision and well-calibrated Surface Potential Electret Reader (SPER) voltmeter for the measurement of the electret voltage. The EIC and its associated accessories are commercially available under the brand name Electret Passive Environmental Radon Monitor (E-PERM®) system by Rad Elec Inc., USA. The device has been widely used in measuring indoor and outdoor radon concentrations because of its rapid readout, without necessarily processing the sensor chemically or microscopically. Also, it has been proved to work at low/high temperatures and low/high humidity (24- 27). More details about the device and associated components; and their applications in measuring radon concentration are described by Kotrappa *et al.* (24); Kotrappa and Steck (25).

Experimental setup

Measurement of initial voltage readings of the electrets

The initial voltage reading of the electrets was measured using the SPER voltmeter inside the laboratory at room temperature and noted as initial voltage (V_i). Thereafter, the devices were transported inside the accompanied tamper-resistant twin box to each study location.

Positioning and hanging of the electrets

At each selected WTPP two different ST electret disks were loaded into two S chambers. The E-PERM® chambers (loaded chambers) was then hung inside the PCG, PKG and STG rooms of the WTPP, at 1 m above the horizontal level. Thereafter, each chamber was turned on (by unscrewing) for it to trap in radon gas and diffus the gas into the chamber through the filtered opening. After seven (7) days the devices were recovered, turned off (screwed) to conserve the trapped and diffused radon gas and then transported back to the laboratory.

Measurement of final voltage readings of the electrets

The final voltage reading of the retracted electrets was measured using the SPER voltmeter reader and recorded as final voltage (V_f). It was ensured that the V_f of the electrets was measured at the same condition as the initial reading as recommended by the manufacturer.

Calculation of radon concentration

The level of radon concentration (R_c) was calculated using Equation (1):

$$R_c(pC_i/L) = \left[\left(\frac{(V_i - V_f) - (IVD \times ED)}{CF \times ED}\right) - (BG \times G)\right] \times ECF \quad (1)$$

where V_i and V_f represent the initial and final voltage readings of the electret, IVD is the inherent voltage discharge of the electret, given as 0.066667 (for standard short-term (SST) configuration), ED is the exposure days (7.125 days), CF is the calibration factor of the E-PERM configuration employed and it was obtained by Equation (2), BG is the background gamma level of each sampling location obtained using a well-calibrated RAD7 detector (a product of DURRIDGE Company Inc., USA), G is the gamma conversion constant, given as 0.087 (for SST E-PERM configuration), and ECF is the elevation correction factor, taken as 1 (since the elevation of Ogbomoso is 347 m = 1138 ft < 4000 ft). The value of R_c was later converted to Bq/m^3, which is the globally recognized unit.

$$CF = A + \left[B \times \ln\left(\frac{V_i + V_f}{2}\right)\right] \quad (2)$$

where A = 0.314473 and B = 0.260619 for standard short-term (SST) E-PERM configuration

Estimation of annual effective dose

The annual effective dose (AED) due to inhalation of radon gas was estimated using Equation (3):

$$AED\ (mSvy^{-1}) = R_c \times EF_{in} \times OF_{in} \times DCF \quad (3)$$

where R_c is the determined radon concentration (Bq/m^3), EF_{in} is the indoor equilibrium factor (0.4), OF_{in} is the indoor occupancy factor (7000 hy^{-1}) and DCF is the dose conversion factor (9 nSv (Bqh/m)$^{-1}$) for radon and its progeny (4).

Data analysis

GraphPad Prism software package (version 9.1.0 (221)) was employed for the analysis of the data and the results were presented as mean ± standard error of the mean (SEM). The data were also subjected to statistical analysis through analysis of variance

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(ANOVA) with Tukey's multiple comparison post-hoc test. $P < 0.05$ was set as the level of significance.

RESULTS

Table 2 presents the radon concentration and the estimated annual effective dose due to inhalation of radon gas by the workers in the rooms of the assayed WTPPs. The radon concentrations obtained ranged from a minimum of 27.02 Bq/m^3 to a maximum of 149.35 Bq/m^3 across all the WTPPs. With the exception of WTPP$_4$ whose concentration is lower in the STG room (34.90 Bq/m^3) but higher in the processing (PCG) room (149.35 Bq/m^3), it was observed that the storage (STG) rooms of other WTPPs had the highest radon concentrations while the packaging (PKG) rooms had the least. The test of significant difference revealed that the WTPPs are not significant from each other at $p < 0.05$ as revealed by the Tukey's multiple comparison test shown in figure 2a. In addition, figure 2b showed the histogram comparing the mean radon concentrations obtained in each of the studied WTPPs with those of reference values. The results obtained for the estimated annual effective dose (AED) as a consequence of the radon concentration ranged from 1.00 to 4.00 mSvy^{-1} for all the WTPPs. The average AED obtained is 1.33 mSvy^{-1} for WTPP$_1$, 1.00 mSvy^{-1} for WTPP$_2$ and WTPP$_5$, and 2.00 for WTPP$_3$ and WTPP$_4$ mSvy^{-1}.

Table 2. Radon concentration (Bq/m^3), and annual effective dose (mSvy^{-1}).

Location Code	Rooms	Radon Concentrations	Mean ± SEM	Annual Effective Dose	Mean ± SEM
WTPP$_1$	PCG	44.96	48.48 ± 12.08	1.00	1.33 ± 0.33
	PKG	29.54		1.00	
	STG	70.94		2.00	
WTPP$_2$	PCG	50.82	50.69 ± 3.73	1.00	1.00 ± 0.00
	PKG	44.16		1.00	
	STG	57.09		1.00	
WTPP$_3$	PCG	52.90	76.40 ± 34.36	1.00	2.00 ± 1.00
	PKG	32.22		1.00	
	STG	144.07		4.00	
WTPP4	PCG	149.35	77.13 ± 36.29	4.00	2.00 ± 1.00
	PKG	47.15		1.00	
	STG	34.90		1.00	
WTPP$_5$	PCG	48.35	41.38 ± 7.18	1.00	1.00 ± 0.00
	PKG	27.02		1.00	
	STG	48.76		1.00	

Legends: WTPP – water treatment and production plants, PCG – processing, PKG – packaging, STG – storage

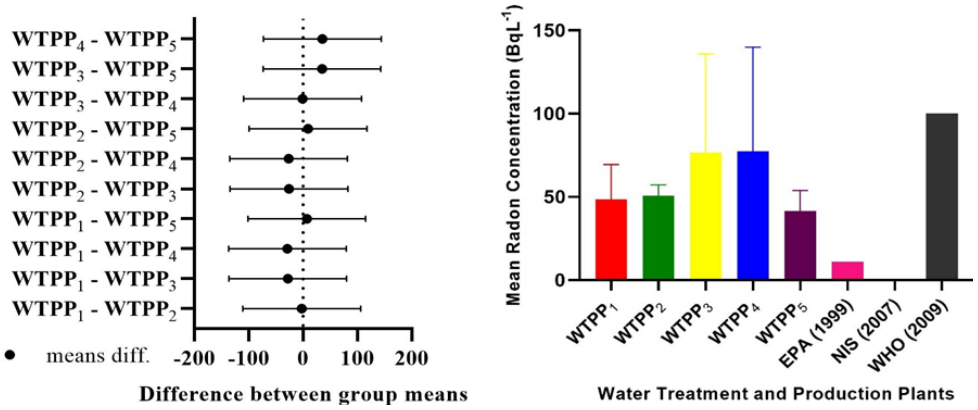

Figure 2: (a) Multiple comparison test of the mean differences of the WTPPs at $p < 0.05$ **(b)** Comparison of mean radon concentration obtained for the investigated WTPPs in Ogbomoso with that of local and international bodies.

DISCUSSION

In general, the results obtained revealed that all the rooms of the WTPPs studied had radon concentrations above the action level of 0.1 Bq/m^3 recommended by Nigerian Industrial Standard (NIS) (28). With the exception of STG in WTPP$_3$ and PCG in WTPP$_4$ that have radon concentration above the World Health Organization (WHO) (8) reference level of 100 Bq/m^3 and the EPA recommended level of 148 Bq/m^3, all other rooms had values below this limit. Although, the test of significant difference revealed that the WTPPs are not significant from each other, however the variation observed in the radon concentrations in all the WTPPs can be attributed to so many reasons such as the geological structure making up the land to which each underground water was obtained for production. The pumping durations, treatment process and production rate among the production facilities also differ, all of which may also contribute to the variation observed in the radon concentrations (29). If the production rate is high, the

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radon reduction rate will be low because the groundwater retention time in the storage tank and the contact time will be short (11). Furthermore, the architecture structure of the buildings in the WTPPs did not give enough space for cross ventilation of air into the rooms of each WTPP, an action that may also contribute to an increase in the indoor radon concentration. The results obtained in this study confirmed the report of previous researchers about the radiological structure of Ogbomoso (7, 20- 21). Furthermore, there are limited studies on the occupational exposure to ^{222}Rn as a result of water treatment and production, however the findings in this study conformed to the reports by Kerber *et al.* (15) and Fisher *et al.*, (17) that there exist elevated radon levels in the indoor air inhaled by the workers during water treatment and production, even far above the EPA's action level of 4.0 pCi/L (148 Bq/m^3).

The results obtained for the AED showed that all the rooms had values higher than the permissible limit of 0.025 mSvy^{-1} for exposure to radon gas via inhalation (4). Also, all the WTPPs had an average AED value that is higher than 1.1 mSvy^{-1} which is the total annual effective dose from inhalation of ^{222}Rn and its decay products present from all sources. The results obtained further confirmed the report by UNSCEAR (4) that on average 90% of the dose attributed to radon in drinking water comes from inhalation rather than ingestion. It was observed that during the seven days period of assessment of each facility, the workers, most especially those working in the processing, packaging, and storage rooms spent about 20 hours of their time per day in each of the assigned rooms to ensure high productivity and maintenance of the machines and facilities. During this period, it is possible that when the radon concentration is at its peak, the workers were also present in the rooms, resulting in inhalation of radon gas by the workers (15). Hence, the workers in the WTPPs investigated may inhale high dose of radon gas which may result in its deposition within the respiratory tract where the sensitive cells along the airways are irradiated with radon short-lived alpha emitters' progenies ^{218}Po and ^{214}Po. Thus, presenting a radiological risk to the workers (3), and even lead to a chronic effect such as lung cancer (12). Based on the results obtained this study adapted the recommendations of Kerber *et al.* (15) as means of lowering occupational exposure to airborne radon in water treatment and production facilities. These are replacing or cleaning the filter media more often to lower the radium levels on the filter media, removing radon concentrations from the backwash and/or aeration areas by exhausting the ambient air outdoors, limiting access to the major rooms during production and provision of adequate ventilation.

CONCLUSION

The radon levels in five different WTPPs in Ogbomoso have been assessed using the E-PERM® system. The radon concentrations and annual effective dose obtained are higher than the action level recommended by both the local and international organizations, thus endangering the workers and necessary action was thereby recommended to reduce the concentrations.

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Conflicts of interests: None.

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