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Article

Direct Measurement of Activity Concentrations and Assess to Cancer Risk of Radon and Thoron in Homes the Towns of Moanda and Franceville, South-East Gabon

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Abstract

The purpose of the present study was to carry out measurements of the activity concentrations of radon (²²²Rn) and thoron (²²⁰Rn) in homes, to calculate the annual effective inhalation dose and the induced risk of lung cancer associated with the exposure to ²²²Rn and ²²⁰Rn, for individuals living in the towns of Moanda and Franceville, in Gabon. One hundred (100) radon-thoron detectors of the brand RADUET were deployed in these localities, 50 per city, i.e., one detector per home. The results of the radon concentrations varied in the range 91-156 Bq m⁻³ in Moanda, with arithmetic and geometric mean values of 113.2 ± 2.8 Bq m⁻³ and 111.8 (1.0) Bq m⁻³, respectively, and in the range 76-139 Bq m⁻³ in Franceville, with arithmetic and geometric mean values of 105.0 ± 1.9 Bq m⁻³ and 104.2 (1.0) Bq m⁻³, respectively. These mean values are above the United Nations Committee on the Effects of Atomic Radiation (UNSCEAR) worldwide average values of 40 Bq m⁻³ (arithmetic mean) and 45 Bq m⁻³ (geometric mean). For thoron, the concentrations varied in the range 3-945 Bq m⁻³, with arithmetic and geometric mean values of 69.5 ± 0.4 Bq m⁻³ and 24.4 (3.9) Bq m⁻³ at Moanda, and in the range 4-78 Bq m⁻³, with arithmetic and geometric mean values of 18.4 ± 0.4 Bq m⁻³ and 11.6 (0.4) Bq m⁻³ in Franceville. This shows that the mean concentration values of thoron were significantly higher than the UNSCEAR world average value of 10 Bq m⁻³. Overall, the highest concentration values were recorded in the town of Moanda and the lowest in the town of Franceville. The dose values estimated in the present study demonstrate that the population in Moanda and in Franceville may be exposed to a relatively significant potential risk of radon-and thoron-induced cancer.

Keywords: radon; thoron; RADUET; activity concentration; effective inhalation dose; cancer risk; Moanda; Franceville; Gabon

1. Introduction

Radon (^{222}Rn) and thoron (^{220}Rn) are colorless, odorless, and chemically inert radioactive gases. They come respectively from the decay chains of uranium (^{238}U) and thorium (^{232}Th) present in the earth's crust [1]. Their disintegration gives rise to elements that are themselves radioactive, to each stabilize at a lead isotope [2]. Radon has been recognized by the World Health Organization (WHO) as a carcinogen agent since 1988 [3], and classified by the International Center for Radiological Protection (IARC) as a definite lung carcinogen agent since 1987 [4]. As an isotope of radon, thoron has almost the same chemical characteristics as radon although fewer studies exist on thoron because of its short half-life (55.6 s) unlike radon (3.8 d). However, it may not be appropriate to neglect the contribution of thoron because ignoring it may lead to an overestimation of radon and/or an underestimation of radiological risk in the environment [5]. Exposure to these gases is a public health problem in many parts of the world. According to an epidemiological investigation by Darby et al consecutive exposure to $100 \text{ Bq}\cdot\text{m}^{-3}$ of radon results in a 16% excess relative risk of lung cancer [6,7]. The World Health Organization recommended that a radon concentration of $100 \text{ Bq}\cdot\text{m}^{-3}$ should be used as a national reference value and stated that this value was justified from a public health effect perspective [7]. The UNSCEAR estimates that 52% of exposure to natural radiation is attributable to radon and thoron, radon contributing to 92% (i.e., 1.15mSv) and thoron to 8% (i.e., 0.1 mSv) [8,9]. This indicate that the contribution of thoron may be considered as negligible. However, a study by Sondzo et al [9,10] showed that the annual effective dose due to exposure to radon and thoron in Djeno, Republic of Congo, was 1.11 mSv, radon and thoron contributing to 51% and 49%, respectively. This demonstrates the fact that the contribution of thoron is not always negligible and highlights the importance of carrying thoron measurements. In this regard, studies are being carried out more and more all over the world to evaluate radon and thoron concentrations and the associated radiation doses indoors [11–14]. Studies for the evaluation of radon and thoron concentrations in dwellings in Moanda and Franceville, Gabon, originate from the work undertaken by Loemba et al in 2018 [15]. This work showed the presence of a high concentration of ^{226}Ra and ^{232}Th , the direct precursors of radon and thoron, in the soil, rocks and water in the Mounana region [15–17]. The main aim of the present study was to provide an answer to the lack of radiological data by directly measuring radon and thoron concentrations in homes in Moanda and Franceville, using RADUET passive radon-thoron discriminating nuclear trace detectors (commercially known as RADUET). The concentrations measured will be used to assess annual effective doses, in order to deduce the risk of lung cancer induced by exposure to these radioactive gases using conventional formulas.

2. Materials and Methods

Study Area

Gabon is a Central African country, the only one in the world to date to have had the privilege of hosting natural nuclear reactors, discovered in the Mounana region in the south-east of the country in 1972 [18]. The areas selected in our study are located close to this region, in the province of Haut-Ogooué where the climate is equatorial. The soil of this province is rich in minerals, notably gold, manganese and uranium which rest on the sedimentary basin of Franceville [18]. Moanda is a town located 41 km from Franceville. This mining town of around 71,099 inhabitants (worldometer, 2024), the capital of Lemboumbi-Leyou department, it is the capital of manganese, the extraction of which is the region's main activity for COMILOG (the world's leading manganese producer). It is the province's second-largest city after Franceville [18]. Franceville is a city in Gabon, the capital of the province of Haut-Ogooué and the Mpassa department, it is the third city in the country in terms of number of inhabitants. It is watered by the Ogooué River as well as the Mpassa River and is located 512 km southeast of Libreville, the capital of the country. Its population is 132,895 inhabitants (worldometer, 2024). The climate is subequatorial due to a short three-month dry season from June to August [19,20].

Deployment and Collect of Detectors

The measurement points were chosen on the basis of random sampling. Data collection took place in two main stages. The first was the awareness campaign on radon, presentation of measuring devices to the concerned populations and deployment of detectors. This stage took place from 04/15/2022 to 04/16/2022 in Moanda and from 04/17/2022 to 19/04/2022 in Franceville (Table 1). One RADUET detector was placed per dwelling in a room frequently occupied, the living room in the present case. The houses involved in the study were all one-level cement brick houses with direct ground contact. The detectors were hung far from openings, between 1.5 and 2 m height from the floor and approximately 20 cm from the wall [21,22]. The second stage was the detector collect campaign. The collect of each device occurred on 06/28/2022 in Moanda and on 06/30/2022 in Franceville, about 2.5 months after the deployment phase. The loss rate was approximately 10%. The samples, grouped and packaged in hermetically sealed plastic packaging, were sent to the Institute of Radiation Emergency Medicine of Hirosaki University in Japan for physicochemical analysis and determination of concentrations.

Table 1. Geolocation of some sampled points and dates of deployment and withdrawal of detectors.

Identification	Longitude (East)	Latitude (South)	Deployment date	withdrawal date
Franceville				
365/607	-1,632709	13,541254	19/04/2022	30/06/2022
303/618	-1,632663	13,542738	19/04/2022	30/06/2022
324/648	-1,640271	13,572224	20/04/2022	01/07/2022
307/613	-1,641713	13,571272	20/04/2022	01/07/2022
Moanda				
359/717	-1,5481	13,215206	15\04\22	28\06\22
353/706	-1,54847	13,212875	15\04\22	28\06\22
371/742	-1,551226	13,21243	16\04\22	29\06\22
368/736	-1,561421	13,216027	16\04\22	29\06\22

Measurement of Radon and Thoron Activity Concentrations

RADUET

To determine radon and thoron concentrations, we used commercially available RADUET monitors, which are passive integrated radon-thoron discriminators, developed at the National Center for Radiological Sciences (NIRS) in Japan, were used [23]. These detectors have two diffusion chambers with different ventilation rates and each chamber contains a 10×10 mm² CR-39 chip. The latter was manufactured by Nagas Landauer, Ltd (Ibaraki, Japan) and used to detect alpha particles emitted by radon and thoron, with a detection limit of 2 Bq m⁻³ for radon and 8 Bq m⁻³ for thoron [24]. The RADUET contains two chambers, the low diffusion rate chamber is made of electron conductive plastic with an interior volume of 30 cm³, the high diffusion rate chamber is also made of the same material, but has six holes in the wall and is covered with an electro-conductive sponge to prevent radon and thoron daughter products as well as aerosols from infiltrating inside (Figure 1) [25]. While one chamber (the low air-exchange rate chamber) measures radon predominantly, the other chamber measures both radon and thoron (the high air-exchange rate chamber) [25,26]. Thoron concentration is then determined by subtracting the result from one detector to the other. The difference in track density between the two CR-39 plates makes it possible to estimate the concentrations of radon and thoron separately. In fact, radon gas can diffuse into the low air-exchange rate chamber through an invisible gap which functions as a high air-diffusion rate barrier. Due to its very short half-life, only a very small amount of thoron goes into the chamber compared to the amount for radon with a longer half-life [27]. Additionally, both radon and thoron can get into the high air-exchange rate chamber.

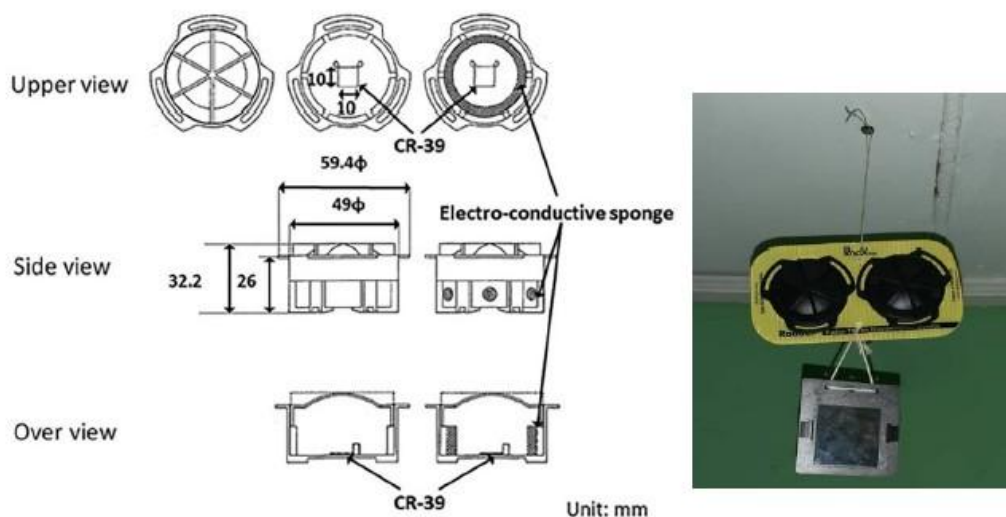


Figure 1. Layout of RADUET type detector (**left**). RADUET detector (**above**) and thoron progeny detector (**below**) hung in a room involved in the study (**right**).

Laboratory Analysis

The CR-39 plates were chemically etched for 24 h in a 6 M NaOH solution (240 g in 1 L of water) at 60 °C. The counting of nuclear tracks was done using a microscope and a camera for observation, images were recorded on a memory card then transferred to an appropriate computer so that they can be read by the image software "Image-J".

The average concentrations of radon \bar{C}_{Rn} and thoron \bar{C}_{Tn} were calculated using the following formulas [9,26,27]:

$$\bar{C}_{Rn} = (d_L - \bar{b}) \times \frac{f_{Tn2}}{t \times (f_{Rn1} \times f_{Tn2} - f_{Rn2} \times f_{Tn1})} - (d_H - \bar{b}) \times \frac{f_{Tn1}}{t \times (f_{Rn1} \times f_{Tn2} - f_{Rn2} \times f_{Tn1})} \quad (1)$$

$$\bar{C}_{Tn} = (d_H - \bar{b}) \times \frac{f_{Rn1}}{t \times (f_{Rn1} \times f_{Tn2} - f_{Rn2} \times f_{Tn1})} - (d_L - \bar{b}) \times \frac{f_{Rn2}}{t \times (f_{Rn1} \times f_{Tn2} - f_{Rn2} \times f_{Tn1})} \quad (2)$$

where:

where \bar{C}_{Rn} and \bar{C}_{Tn} are the mean concentrations of radon and thoron during the exposure period in Bq.m⁻³. d_L and d_H are the total alpha track densities (track.m⁻²) taken from the CR-39 detectors of low and high air-exchange rate chambers. f_{Rn1} and f_{Tn1} are the radon and thoron calibration coefficients for the low air-exchange rate chamber in tracks.m⁻².kBq⁻¹.m³.h⁻¹. f_{Rn2} and f_{Tn2} are the radon and thoron calibration coefficients for the high air-exchange rate chamber in tracks.m⁻².kBq⁻¹.m³.h⁻¹. t is the exposure time in hours and b is the background track density of the CR-39 detector in tracks.m⁻². It should be noted that the low air-exchange rate chamber limits diffusion of thoron into the chamber, therefore, $f_{Rn1} \gg f_{Tn1}$. The high air-exchange rate chamber is designed such that both radon and thoron can diffuse into the chamber easily, and $f_{Rn2} \sim f_{Tn2}$. [28–30]. The calibration procedure for the RADUETs used in this study was detailed by Kranrod et al (2020) [30].

Calculation of Annual Effective Dose and Cancer Risk Index

Annual Effective Inhalation Dose

The formulas used are [12,22,27]:

- For radon

$$E_{Rn} = \bar{C}_{Rn} \times F_{eqRn} \times e_{Rn} \times F_{occ} \times T \times 10^{-6} \quad (3)$$

- For thoron

$$E_{Tn} = \bar{C}_{Tn} \times F_{eqTn} \times e_{Tn} \times F_{occ} \times T \times 10^{-6} \quad (4)$$

where:

$$F_{eqTn} = \frac{EETC}{\bar{C}_{Tn}} \quad (5)$$

- E_{Rn} is the effective inhalation dose for radon;
- E_{Tn} effective inhalation dose for thoron;
- $EETC$ ($Bq\ m^{-3}$) is the measured activity concentration of thoron progeny determined in reference [31];
- \bar{C}_{Rn} and \bar{C}_{Tn} ($Bq\ m^{-3}$) are the measured activity concentrations of radon and thoron, respectively;
- F_{epRn} and F_{eqTn} (unitless) are the equilibrium factors for radon and thoron, respectively; F_{epRn} was taken equal to 0.4 and F_{eqTn} was determined by experimental measurements, $F_{eqTn} = 0.183$ (for Franceville), $F_{eqTn} = 0.184$ (for Moanda) [22];
- e_{Rn} and e_{Tn} ($nSv(Bq\ h\ m^{-3})^{-1}$) are the effective dose conversion factors for radon and thoron progeny (respectively equal to 9 and 40);
- F_{occ} (unitless) is the occupancy factor recommended for the studied area, equal to 0.6 [32];
- T (h) is the exposure time which was adjusted to one years, i.e., 8760 h.

Excess Lifetime Cancer Risk

The Excess Lifetime Cancer risk (ELCR) was computed as follows [11,28,29]:

$$ELCR = E_{Rn} \times D_G \times R_F \quad (6)$$

where:

- E_{Rn} (mSv) is the annual effective inhalation dose due to exposure to indoor radon;
- D_G (y) is the average lifespan estimated in Gabon to be 63.4 years [29];
- R_F (Sv^{-1}) is the nominal probability coefficient for cancer risk whose value is 5.5×10^{-2} [31].

3. Results

Figures 2 and 3 show that radon and thoron concentrations measured in Moanda and Franceville follow a lognormal distribution.

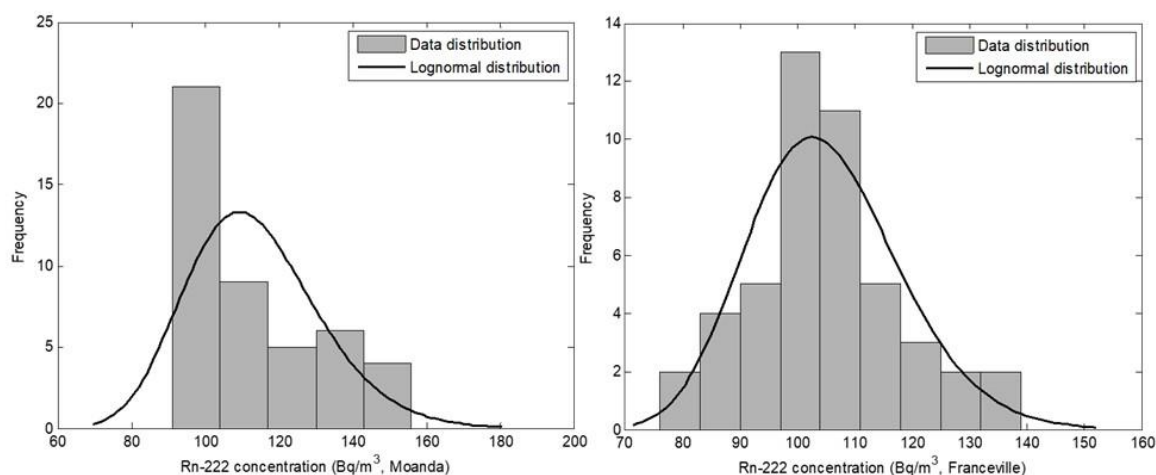


Figure 2. Distribution of radon activity concentrations in Moanda and Franceville.

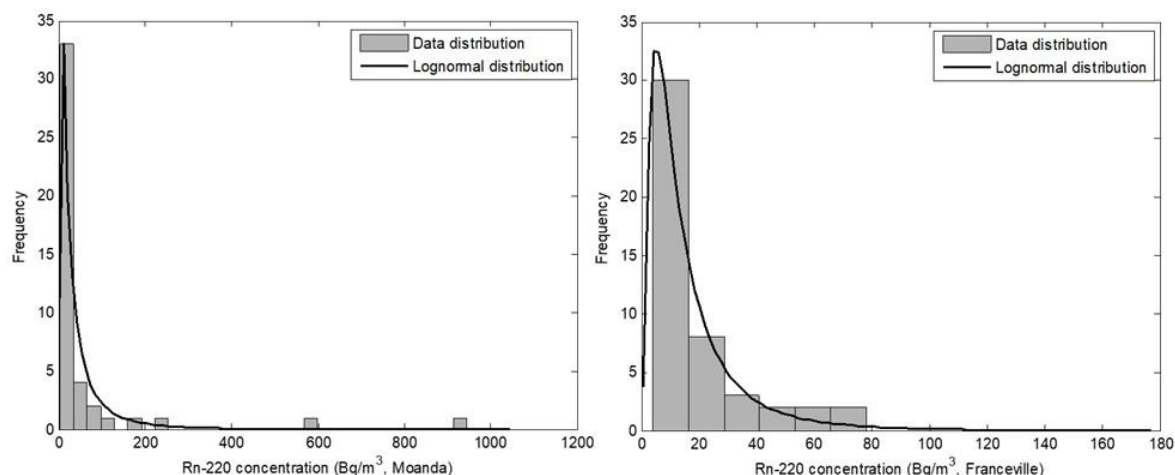


Figure 3. Distribution of thoron activity concentrations in Moanda and Franceville.

Table 2 shown us the minimum and maximum concentrations, the arithmetic, geometric means and median in Bq m^{-3} of radon and thoron measured in homes in Moanda and Franceville.

Table 2. Concentrations (Bq m^{-3}) of radon and thoron measured in homes in Moanda and Franceville.

Cities	Moanda		Franceville	
Statistical parameters	Radon	Thoron	Radon	Thoron
MIN	90.9	3	75.9	4
MAX	156.2	945	139.0	78
AM \pm SD	113.2 ± 2.8	69.0 ± 0.4	105.0 ± 1.9	18 ± 0.4
GM (GSD)	111.8 (1.0)	24.4 (3.9)	104.2 (1.0)	12.2 (0.4)
MEDIAN	105.8	22	104.3	11

Figure 4 shown On the other hand, the boxplots of radon and thoron activity concentrations measured in the cities of Moanda and Franceville, with the World Health Organization and International Commission on Radiological Protection (ICRP) reference level for activity concentrations to radon and thoron.

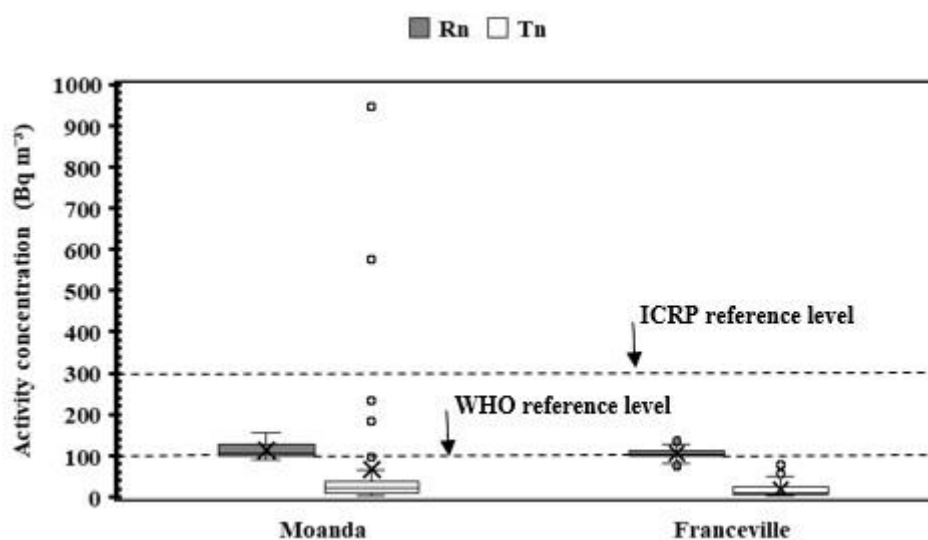


Figure 4. Boxplots of radon and thoron activity concentrations measured in the cities of Moanda and Franceville.

In Table 3 we have the minimum and maximum annual effective dose inhalation, the arithmetic, geometric means and median in mSv of radon and thoron measured in homes in Moanda and Franceville.

Table 3. Annual effective inhalation dose in (mSv) for radon and thoron in homes in Moanda and Franceville.

Statistical parameters	Moanda		Franceville	
	Radon	Thoron	Radon	Thoron
MIN	1.7	0.1	1.4	0.02
MAX	3.0	5.7	2.6	0.8
AM \pm SD	2.1 \pm 0.05	1.0	2.0 \pm 0.04	0.4
GM \pm (GSD)	2.1 (1.0)	-	2.0 (1.0)	-
MEDIAN	2.0	0.6	2.0	0.3

4. Discussion

Radon and Thoron Concentrations

Of the 100 detectors deployed, i.e., 50 per city, 44 were recovered in Moanda and 47 in Franceville, the remaining (10) were considered as losses. Figures 2 and 3 show that radon and thoron concentrations measured in Moanda and Franceville follow a lognormal distribution. As shown in Table 2 (and Figure 4), in Moanda, the lowest radon concentration was 91 ± 1 Bq m⁻³ (Cit  CB) and the highest was 156 ± 1 Bq m⁻³ (Cit  Alliance). In Franceville, the lowest and highest radon concentrations measured were 76 ± 1 Bq m⁻³ (Maba military camp) and 139 ± 1 Bq m⁻³ (Potos neighbourhood), respectively. For thoron, the concentrations varied in the range 3-945 Bq m⁻³ (Oasis neighbourhood) in Moanda and in the range 4-78 Bq m⁻³ in Franceville. Figure 4 also show a significant number of outliers in the distribution of thoron concentrations measured in Moanda that may be considered as abnormal values.

The arithmetic and geometric means for radon were, respectively, 113.2 ± 2.8 Bq m⁻³ and 111.8 (1.0) Bq m⁻³ in Moanda, and 105.0 ± 1.9 Bq m⁻³ and 104.2 (1.0) Bq m⁻³ in Franceville. These average values were above 100 Bq m⁻³, the WHO reference level [3], but they were below 300 Bq m⁻³, the reference level recommended by the International Commission on Radiological Protection (ICRP) [31,39]. Compared to the worldwide arithmetic and geometric mean values, 40 Bq m⁻³ and 45 Bq m⁻³, respectively [12–14], the arithmetic and geometric mean values determined in this study in Moanda and Franceville are greater than twice the UNSCEAR worldwide average values. Concerning thoron, the arithmetic and geometric mean values were, respectively, 69.0 ± 0.4 Bq m⁻³ and 24.4 ± 3.9 Bq m⁻³ in Moanda, and 18 ± 0.4 Bq m⁻³ and 12.2 ± 0.4 Bq m⁻³ in Franceville. These average values are 1.2 to 6.9 times greater than the UNSCEAR world average value of 10 Bq m⁻³ [12]. The main reason that may explain the high values of radon and thoron concentrations observed in Moanda and Franceville, compared to the UNSCEAR worldwide estimated values, is that these two cities are located in the province of Haut-Ogoou , characterized by the geological formation called the Francevillian, rich in elements such as uranium, manganese and others.

Overall, only 5 homes (11.4%) had thoron concentrations greater than 100 Bq m⁻³ and 1 home had thoron concentration much greater than 300 Bq m⁻³. The results obtained showed a predominance of thoron than radon in Moanda, unlike in Franceville. We can assume that ²³²Th may be more abundant than ²³⁸U in Moanda. A thorough characterization of Moanda soil may show to what extent this finding holds.

Annual Effective Inhalation Dose

The annual effective inhalation dose values estimated for radon were in the range 1.7-3.0 mSv with an arithmetic mean value of 2.1 ± 0.05 mSv for Moanda, and in the range 1.4-2.6 mSv with an arithmetic mean value of 2.0 ± 0.04 mSv for Franceville (Table 3). These average effective inhalation dose values are above the UNSCEAR determined value of 1.1 mSv [12]. For thoron, the annual

effective inhalation dose values obtained varied in the range 0.1-5.7 mSv, with an arithmetic mean value of 1.0 mSv in Mounana, and in the range 0.02-0.8 mSv with an arithmetic average value of 0.4 mSv in Franceville. These values are higher than the UNSCEAR estimated value of 0.09 mSv [12]. Furthermore, the median values indicate that 50% of the homes sampled have a dose greater than or equal to 0.6 mSv in Moanda and 0.3 mSv in Franceville.

Excess Lifetime Cancer Risk

The ELCR is the probability that an individual will develop or die from cancer during their lifetime due to exposure to radon. The ELCR range obtained for radon and for Moanda was 6-10 %, with an average value of 7 %. For Franceville, ELCR range was 5-9 % with an average value of 7 %. The ELCR values determined in this study are higher than the action level of 1.3% given by the United States Environmental Protection Agency (EPA) [33]. However, the conversion coefficient for this rate in Gabon has not yet been established. It is worth noting that no cancer risk coefficient has been specifically determined for Gabon. Therefore, the ELCR values estimated in the present study may have been overestimated. Furthermore, the cancer risk coefficient value ($R_F = 5.5 \times 10^{-2} \text{ Sv}^{-1}$) used to compute ELCR in this study was derived from different types of ionizing radiation exposure, not only radon exposures. Considering the first results obtained in this study, radiation protection remedial measures should be considered.

Comparison with Selected Studies in the Literature

Several studies on radon and thoron have been carried out around the world (Table 4). They used different types of appropriate detectors to measure activity concentrations in dwellings.

Table 4. Comparison with selected studies on radon in the literature.

Country	Place	AM (Bq m ⁻³)	GM (Bq.m ⁻³)	Range (Bq m ⁻³)	References
South Africa	West	132	-	28 - 465	[35]
South Africa	East	37	-	8 - 998	[35]
South Korea	Bonghwa County	49	37	-	[34]
Spain	-	95	56.6	10 - 15400	[37]
Turkey	-	81	57	1 - 1400	[38]
Cameroon	Southern Adamawa	108	102	43 - 270	[32]
Cameroon	Poli, Lolodorf	103	102	75 - 137	[25]
Cameroon	Ebolowa	135.6	63	23-2620	[10]
Cameroon	Mvangan	64	60	36-150	[11]
Congo	Djeno	29	28	20-44	[9]
Gabon	Moanda	113.2	111.8	90.9 - 156.2	This study
Gabon	Franceville	105.0	104.2	75.9 - 139.0	This study

The results obtained in our study are close to those of two regions in Cameroon (southern Adamawa and Poli/Lolodorf) [25,32]. They are about twice the concentration values measured in Mvangan (Cameroon) and Bonghwa County (South Korea), and lower (arithmetic mean) than those determined in Ebolowa (Cameroon) and in west south Africa [10,11,34,35]. They are up to about 4 times the concentration values obtained in Djeno in Congo [9].

Thoron concentrations measured in this study (Table 5) in Moanda are intermediate (arithmetic means) between those determined in Djeno (Congo) and Lolodorf (Cameroon).

Table 5. Comparison with selected studies on thoron in the literature.

Country	Place	AM (Bq.m ⁻³)	GM (Bq.m ⁻³)	Range (Bq.m ⁻³)	MED (Bq.m ⁻³)	References
India	Ambala	-	-	1.2 - 69.2	14.4	[36]

Cameroon	Lolodorf	149	105	18 - 451	10	[34]
Congo	Djeno	29	28	20-44	-	[9]
Gabon	Moanda	69.0	24.4	4 - 78	22	This study
Gabon	Franceville	18	12.2	3 - 945	11	This study

Values (arithmetic mean, geometric mean, median) determined in this study in Franceville are globally lower than those measured elsewhere.

The variation in concentration values measured in the present study and those determined in the literature may be due to differences or similarities in the soil geology, meteorology, climate, type of housing, and the lifestyle of the populations [27,39].

5. Conclusion

The aim of this study was to carry out direct measurements of radon and thoron concentrations in dwellings in Moanda and Franceville (Gabon), and to calculate the annual effective inhalation dose and the induced cancer risk associated with the exposure to thoron and radon in these localities. Regarding radon, the study revealed that the geometric and arithmetic average concentrations estimated in our study were significantly higher than the UNSCEAR world average values. These average values were also above the WHO reference level but they remained below the ICRP reference level. Concerning thoron, the arithmetic and geometric mean values were up to 6.9 times greater than the UNSCEAR world average value. About 11% of homes had thoron concentrations greater than the WHO reference level for radon and, in one instance, thoron concentration exceeded the ICRP reference level for radon. Furthermore, the results obtained showed a predominance of thoron than radon in Moanda. The average effective inhalation dose values due to radon and thoron exposures were higher than the UNSCEAR determined values for radon and thoron. The excess lifetime cancer risk values estimated in the present study were higher than the EPA action level. The dose values and ELCR estimated in the study demonstrate that the population in Moanda and in Franceville may be exposed to a relatively significant potential risk of radon-and thoron. and their progeny induced cancer. and their progeny. We recommend more representative studies, also for the case of other dwelling types, to confirm or invalidate these conclusions for the area, but also epidemiological studies to make these results and conclusions more realistic.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “Conceptualization, Sylvere Yannick Loemba Mouandza; methodology, Sylvere Yannick Loemba Mouandza; software, Tokonami Shinji; validation, Tokonami Shinji; formal analysis, Sylvere Yannick Loemba Mouandza and Ronixe Bipolo Djeune; investigation, Sylvere Yannick Loemba Mouandza, Evaldie-Domonique Durastanti-Rabenga Mombo, Ndong Wilfried and Ronixe Bipolo Djeune; resources, Philippe Ondo Meye; data curation, Philippe Ondo Meye; writing—original draft preparation, Sylvere Yannick Loemba Mouandza and Philippe Ondo Meye; visualization, Beaud Conrad Mabika Ndjembidouma; supervision, Sylvere Yannick Loemba Mouandza and Ndong Wilfried; project administration, Thierry Blanchard Ekogo, Tokonami Shinji and Germain Hubert Ben-Bolie; funding acquisition, Saïdou. All authors have read and agreed to the published version of the manuscript.

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