



Public Exposure to Natural Radiation and the Associated Increased Risk of Lung Cancer in the Betare-Oya Gold Mining Areas, Eastern Cameroon

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ABSTRACT

Background: This study aims to reevaluate natural radiation exposure, following up on our previous study conducted in 2019, and to assess the associated risk of lung cancer to the public residing in the gold mining areas of Betare-Oya, east Cameroon, and its vicinity.

Materials and Methods: Gamma-ray spectra collected using a 7.62 cm×7.62 cm in NaI(Tl) scintillation spectrometer during a car-borne survey, *in situ* measurements and laboratory measurements performed in previous studies were used to determine the outdoor absorbed dose rate in air to evaluate the annual external dose inhaled by the public. For determining internal exposure, radon gas concentrations were measured and used to estimate the inhalation dose while considering the inhalation of radon and its decay products.

Results and Discussion: The mean value of the laboratory-measured outdoor gamma dose rate was 47 nGy/hr, which agrees with our previous results (44 nGy/hr) recorded through direct measurements (*in situ* and car-borne survey). The resulting annual external dose (0.29 ± 0.09 mSv/yr) obtained is similar to that of the previous study (0.33 ± 0.03 mSv/yr). The total inhalation dose resulting from radon isotopes and their decay products ranged between 1.96 and 9.63 mSv/yr with an arithmetic mean of 3.95 ± 1.65 mSv/yr. The resulting excess lung cancer risk was estimated; it ranged from 62 to 216 excess deaths per million persons per year (MPY), 81 to 243 excess deaths per MPY, or 135 excess deaths per MPY, based on whether risk factors reported by the U.S. Environmental Protection Agency, United Nations Scientific Committee on the effects of Atomic Radiation, or International Commission on Radiological Protection were used, respectively. These values are more than double the world average values reported by the same agencies.

Conclusion: There is an elevated level of risk of lung cancer from indoor radon in locations close to the Betare-Oya gold mining region in east Cameroon. Therefore, educating the public on the harmful effects of radon exposure and considering some remedial actions for protection against radon and its progenies is necessary.

Keywords: Air Absorbed Dose Rate, External Dose, Inhalation Dose, Excess Lung Cancer Risk

Original Research

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Introduction

Human beings are continuously exposed to ionizing radiation exuded by naturally occurring radiative material (NORM) and radon gas found in the environment [1]. Exposure to such background radiation is a contributing factor to the occurrence of serious health problems such as lung cancer. An increased level of radiation exposure compared to natural exposure levels may occur owing to naturally occurring (e.g., earthquakes) or human-induced (e.g., mining activities) phenomena [2, 3]. Mining is typically performed using surface or underground techniques. These mining activities thus make it possible to bring to the surface of the earth not only desired minerals but also NORM-containing waste material that may seriously pollute the environment and affect human health [4]. The main components of NORM are typically terrestrial radionuclides: ^{40}K , ^{238}U , and ^{232}Th . In particular, the radon isotopes ^{222}Rn (radon) and ^{220}Rn (thoron), which are members of the ^{238}U and ^{232}Th decay chains, respectively, and their decay products are often deemed the main contributors to the general population's exposure to radiation. From the perspective of protection from radiation, determining the level of public exposure to radiation before mining is essential to accurately assess the radiological impact of said mining on the local population.

Cameroon has one of the richest subsurfaces in Central Africa, endowed with abundant mineral resources of international value such as gold, diamond, bauxite, rutile, uranium, tin, cobalt, nickel, manganese, and iron [5]. To date, the exploitation of these natural resources has operated on an artisanal and semimechanized basis. However, according to the government, the mining sector will play a major role in Cameroon's "Vision 2035" strategy to establish the country as an emerging market. Thus, multiple actions such as the adoption of a new mining code in 2017 [6] have been taken by the government to better organize and promote this sector. In addition, the establishment of a modernized mining cadastre, which began in 2011, has revealed more than 300 new mining deposits as of 2019 [5].

Gold mining in Cameroon dates back to 1934 under colonial administration. Most of the 140 sites identified with gold deposits in Cameroon are located in the Eastern region of the country, in particular in the cities of Yokadouma, Garoua-Boulai, Batouri, and Betare-Oya. For most of the 20th century, the gold mining performed here was purely artisanal, but transitioned into a semi-industrial activity in the early 2000s,

and over the past decade it has yielded an annual production of around 20,000 kg. Public exposure to radiation from such mining activity in Eastern Cameroon has been the subject of few studies [7, 8]. The present study aims to not only reevaluate public exposure to natural radiation, based on measurements obtained from previous studies, but also to assess for the first time the lung cancer risk due to this exposure.

Materials and Methods

1. Survey Area and Route

The absorbed dose rates in air (nGy/hr) from natural radionuclides (^{40}K , ^{238}U series, and ^{232}Th series) and indoor radon isotopes and their progeny (radon and thoron) were measured from July 8th to 10th and from July 9th to September 30th 2016 respectively in Betare-Oya town and its vicinity in Eastern Cameroon. The survey routes (Fig. 1) were selected inside Betare-Oya city and on the main roads linking Betare-Oya to its surrounding localities (Ndokayo and Mali). The main road from Ndokayo to Betare-Oya town is asphalt, while Betare-Oya is connected to Mali village by a dirt road. The route map was drawn using the generic mapping tools created by Wessel and Smith [9] and the weather conditions were sunny or cloudy throughout the survey. Intensive gold mining in this region has caused serious environmental disruption, leaving a landscape strewn with deadly open pits and potentially leading to increased levels of radiation and radioactive contamination.

2. External Exposure to Natural Radiation

(1) Car-borne, *in situ* and laboratory measurements of outdoor absorbed dose rate in air

A car-borne survey is a convenient method for the evaluation of radiation dose across a wide area over a short period [10–12]. For this study, measurements were recorded using a 7.62 cm × 7.62 cm in NaI(Tl) scintillation spectrometer (EMF-211; EMF Japan Co.) and a global positioning system (GPS) setup inside a car (Land Cruiser 79 Double Cabin Pick-Up; Toyota). Measurements of the count rate and GPS data were recorded at 30 seconds intervals while driving along the survey road at a speed of around 40 km/hr (Fig. 1). The car body correction (shielding factor [SF]) was estimated as the ratio of the count rate inside the car to the count rate outside the car. Count rates were measured at consecutive 30 seconds intervals over a total recording period of 2 minutes inside and outside the car at 10 locations. The outdoor absorbed dose

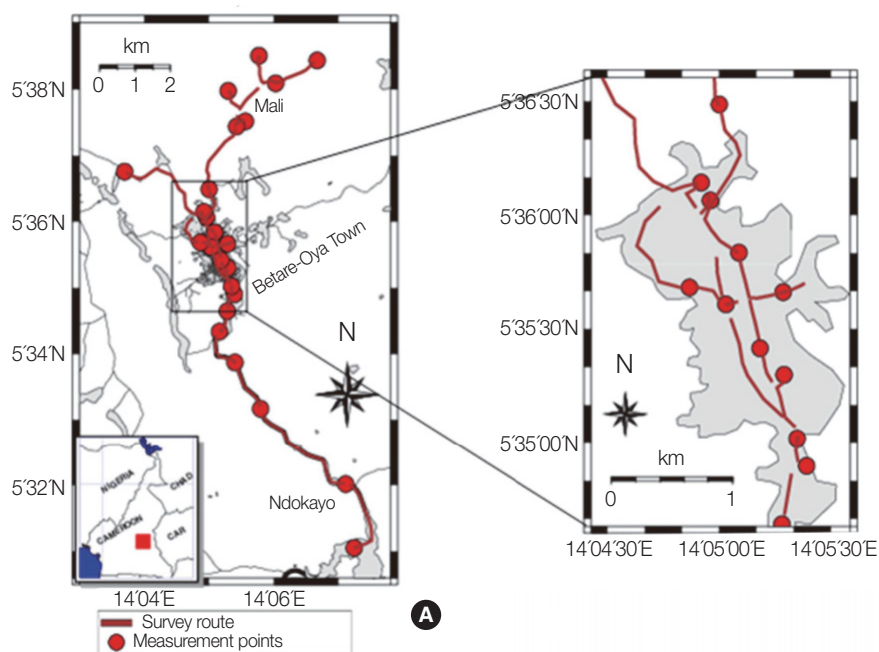


Fig. 1. Map of survey route (A) across entire study area, and (B) within Betare-Oya town, indicating locations where gamma-ray measurements were performed using a NaI(Tl) scintillation detector [7].

rate in air 1 m above the ground surface, can be estimated using Equation (1):

$$D_{ab_car} = 2N_{in} \times SF \times DRCF \quad (1)$$

where N_{in} is the number of counts inside the car obtained during a 30-second measurement. The dose rate conversion factor ($DRCF$) is the slope of the regression line fitted to a graph of measured dose rates plotted against the total count rates of the NaI(Tl) detector given by Ngoa Engola et al. [7].

In situ measurements were carried out using the same NaI(Tl) detector as that used for the car-borne survey. For that, measurements of gamma-ray pulse height distributions were performed at 1 m above the ground surface outside the car for 15 minutes at 24 measurement points (Fig. 1). These 24 measurement points were selected based on high ambient dose rates observed at specific points along the study route. For the calculation of activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K , and estimation of outdoor absorbed dose rate in air, the 22×22 response matrix method, developed by Minto [13, 14] was used to unfold the gamma-ray pulse height distributions.

Laboratory measurements of the activity concentrations of radionuclides, used to evaluate the dose rate absorbed in air in the present work, were carried out by Dallou et al. [15]. Details of sampling, conditioning, and activity concentration

calculations are well described in their publication [15], with an outline described here. In their study, Dallou et al. [15] collected 32 soil samples from seven gold mining sites in Eastern Cameroon, including five sites located in the gold-bearing area of Betare-Oya. Gamma-ray spectrometry measurements of these soil samples were performed with a Canberra NaI(Tl) detector (Model 802), with a crystal size of $7.6 \text{ cm} \times 7.6 \text{ cm}$ and a resolution of 7.5% at 667 keV, housed inside a thick lead shield (5 cm) to minimize background radiation. The detector was coupled to a computer-based multichannel analyzer which was used for the acquisition of data and analysis of gamma-ray spectra. Spectra were acquired and analyzed using GENIE 2000 software (Mirion Technologies). Thus, from the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K measured in soil samples, the absorbed dose rate in air was evaluated according to Equation (2):

$$D_{ab_Lab} = 0.462 \times A_u + 0.604 \times A_{Th} + 0.0417 \times A_K \quad (2)$$

where A_u , A_{Th} , and A_K are the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K respectively in Bq/kg. The coefficients of 0.462, 0.604, and 0.0417 are conversion factors (absorbed dose rate in air per unit activity per unit of soil mass) in units of (nGy/hr)/(Bq/kg) evaluated for ^{238}U -series, ^{232}Th -series, and ^{40}K respectively [16].

2) External annual effective dose recalculation

The external annual effective dose E_{ext} (mSv/yr) due to gamma-rays from primordial radionuclides in the study area was calculated using Equation (3) [7]:

$$E_{ext} = F_c \times D \times T \times [(1 - I_{in}) + SF \times I_{in}] \quad (3)$$

where F_c is the dose conversion factor from the dose rate to the external effective dose for adults (0.7 Sv/yr), D is the absorbed dose rate in air, I_{in} is the indoor occupancy factor (OF , 0.6), which implies that people spend 40% of their time outdoors. SF is the experimental SF of buildings, which is given by the rate of indoor and outdoor dose [7]. T is the number of hours in 1 year (8,760 hr/yr).

3. Internal Exposure to Natural Radiation

1) Indoor radon, thoron, and thoron progeny measurements

Passive integrated radon-thoron discriminative detectors, namely the RADUET detector developed at the National Institute of Radiological Sciences (NIRS) in Japan, alongside the thoron progeny detector developed by Zhuo and Iida and improved by Tokonami et al. [17, 18] were used to simultaneously measure indoor radon, thoron, and thoron progeny concentrations (Fig. 2). RADUET detectors have two diffusion chambers with different ventilation rates (i.e., one with a low air-exchange-rate and one with a high air-exchange-rate). Each chamber contains a CR-39 plate 10 mm × 10 mm in size (RADUET; Radosys Ltd.) for detecting alpha particles emitted from radon and thoron, as well as their progeny. The thoron progeny deposition rate detector is made of stainless steel and consists of CR-39 plates covered with an aluminized Mylar film of 71 mm thickness (Ganapathy Industries), designed for the discrimination of high-energy alpha parti-

cles, especially those emitted by ^{212}Po (8.78 MeV). Calibration of the RADUET monitor was performed by placing the detector inside a calibration chamber. Calibration coefficients were then estimated based on the correlation between the recorded alpha particle track density and the time-integrated radon and thoron concentrations [19, 20].

Fifty dwellings studied during the previous survey [8] were selected to estimate indoor exposures to radon isotopes and their progenies. RADUET [17] and thoron progeny [18] detectors were deployed in each house and suspended from the bedroom ceiling at a height of 1.5 to 2.0 m from the floor and 0.5 m from the wall. After a measurement period of 3 months, the detectors were collected and sent to Hirosaki University for the evaluation of alpha particle tracks.

The average radon ($\overline{C_{Rn}}$), thoron ($\overline{C_{Tn}}$), and thoron progeny (N_{TnP}) concentrations were calculated using Equations (4), (5), and (6) respectively, as reported by ISO16641 [21].

$$\overline{C_{Rn}} = (d_L - \bar{b}) \times \frac{f_{Tn2}}{t \times (f_{Rn1} \times f_{Tn2} - f_{Rn2} \times f_{Tn1})} - (d_H - \bar{b}) \times \frac{f_{Tn1}}{t \times (f_{Rn1} \times f_{Tn2} - f_{Rn2} \times f_{Tn1})} \quad (4)$$

$$\overline{C_{Tn}} = (d_H - \bar{b}) \times \frac{f_{Rn1}}{t \times (f_{Rn1} \times f_{Tn2} - f_{Rn2} \times f_{Tn1})} - (d_L - \bar{b}) \times \frac{f_{Rn2}}{t \times (f_{Rn1} \times f_{Tn2} - f_{Rn2} \times f_{Tn1})} \quad (5)$$

$$N_{TnP} = C_{TnP} \times F_{TnP} \times T - N_{B2} \quad (6)$$

d_L and d_H represent alpha track densities (track/cm²) for the low and high air-exchange-rate chambers, respectively. The conversion factors from alpha track densities to radon and thoron activity concentrations for the high exchange-rate air chamber [(track/cm² · hr)/(Bq/m³)] are given by f_{Rn2} and f_{Tn2} , respectively. In Equations (4) and (5), t represents exposure time (hr) and \bar{b} represents the background alpha track density (track/cm²) recorded by the CR-39 detector. In Equation (6), N_{B2} is the background alpha track density of the CR-39

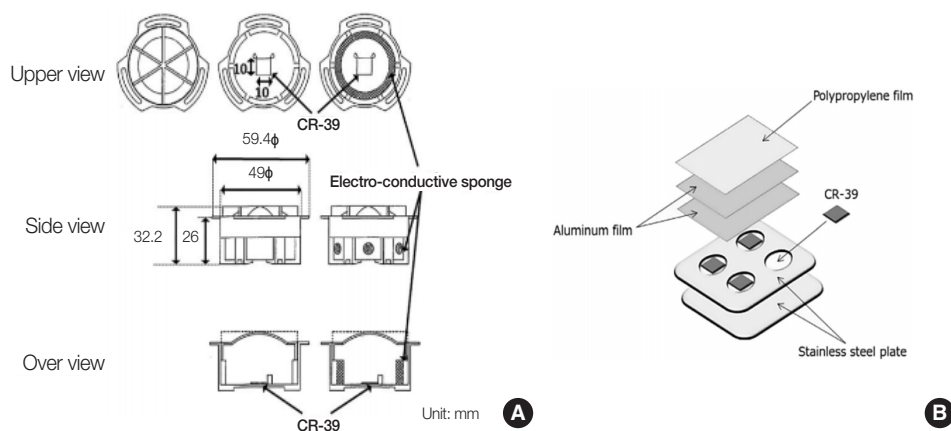


Fig. 2. Overview of the RADUET (A) and the thoron progeny monitor (B) [17, 18].

plate in the thoron progeny deposition detectors, T is the exposure time, and F_{TnP} the conversion factor for the thoron progeny deposition detector.

2) Inhalation dose assessment

To assess inhalation doses (mSv/yr), Equations (7) and (8), which take into account the dissolution of the radon and thoron gas in blood [16], were used.

$$E_{RnP} = (0.17 + DCF_{Rn} \times F_{Rn}) \times C_{Rn} \times 8760 \times 0.6 \times 10^{-6} \quad (7)$$

$$E_{TnP} = (0.11 \times C_{Tn} + DCF_{Tn} \times C_{TnP}) \times 8760 \times 0.6 \times 10^{-6} \quad (8)$$

C_{Rn} , C_{Tn} , and C_{TnP} are activity concentrations of radon, thoron, and thoron progeny respectively. Dose coefficients of 0.17 and 0.11 nSv/(Bq · hr/m³) were used for radon and thoron gas dissolved in blood, respectively. DCF_{Rn} and DCF_{Tn} are the inhalation dose conversion factors (9 and 40 nSv/Bq · hr/m³) for radon and thoron progeny, respectively). An OF of 0.6 was assumed for the studied areas. F_{Rn} represents the equilibrium factor (EF) for radon (0.4) [16], 8760 is a factor that adjusts exposure time to 1 year, expressed in hours. The International Commission on Radiological Protection (ICRP) conversion factors for radon and thoron progenies (16.8 and 107 nSv/Bq · hr/m³, respectively) were also used to determine the inhalation dose using a dosimetric approach [22].

Table 1. Risk Factors as Given by Different Scientific Committees and Agencies

International committees/ Agencies	Cancer deaths PMP per WLM	Reference
US EPA (1986)	115–400	[26, 27]
ICRP (1987)	250	[28]
UNSCEAR (1988, 1993)	150–450	[1]

PMP, per million person; WLM, working level month; US EPA, U.S. Environmental Protection Agency; ICRP, International Commission on Radiological Protection; UNSCEAR, United Nations Scientific Committee on the effects of Atomic Radiation.

Table 2. The Activity Concentrations of ²³⁸U, ²³²Th, and ⁴⁰K and the Outdoor Absorbed Gamma Dose Rate in Air Estimated for the Car-Borne Survey, *in situ* Measurements, and Laboratory Measurements of Soil Samples

Measurement type	Concentration (Bq/kg)			The outdoor absorbed dose rate (nGy/hr)
	²³⁸ U	²³² Th	⁴⁰ K	
Car-borne survey	-	-	-	44 ± 5 (23–80)
<i>In situ</i> measurements	37 (20–63)	32 (13–87)	197 (16–414)	44 ± 7 (25–83)
Laboratory measurements	40 (25–57)	29 (18–41)	266 (159–435)	47 (29–69)
World average	33 (16–110)	45 (11–64)	420 (140–850)	60

Values are presented as median (range) or mean ± standard deviation (range).

4. Excess Lung Cancer Risk Estimates

Several epidemiological studies on underground miners have shown that long term exposure to radon increases the risk of lung cancer. Indoor radon exposure is responsible for 6% to 15% of all lung cancer deaths [23] and, according to International Agency of Research on Cancer, it is the second leading risk factor for lung cancer after tobacco [24]. In the present study, the excess lung cancer risk (ECR) risk model was used for the calculation of lung cancer risk resulting from indoor radon exposure. ECR is defined as the number of additional deaths per million persons per year (MPY) from lung cancer as a result of exposure to radon and its progeny [25]. The ECR was estimated using Equation (9) [25–27]:

$$ECR = EF \times OF \times Risk\ Factor \times WLM \quad (9)$$

where EF is the EF between radon and its progenies, OF is the fraction of time that people spend indoors, and WLM is the Working Level Month. For this study, default values of 0.4 for the radon EF and 0.8 for the OF , as given by United Nations Scientific Committee on the effects of Atomic Radiation (UNSCEAR) [16], were used. The risk factor given by various international committees/agencies (UNSCEAR, ICRP, and U.S. Environmental Protection Agency [US EPA]) describes the lifetime risk of lung cancer mortality due to lifetime exposure to radon and its progeny (Table 1) [1, 26–28]. In other words, it is the number of lung cancer deaths per million persons per WLM. A conversion factor of 73.9 Bq/m³ = 1 WLM/yr was used to convert radon concentration level into WLM.

Results and Discussion

1. External Exposure to Natural Radiation

1) Car-borne, *in situ*, and laboratory measurements of activity concentrations and related outdoor absorbed dose rate in air

Table 2 shows activity concentrations of the naturally oc-

curing radionuclides ^{226}Ra (^{238}U), ^{232}Th , and ^{40}K , and the outdoor absorbed dose rate obtained by the car-borne survey, *in situ* measurements, and the laboratory-based gamma spectrometry measurements of soil samples. Results obtained by the three techniques showed a low amount of deviation, despite the fact that different locations were used for the *in situ* measurements and the soil sampling. For activity concentrations, the ratios between *in situ* and laboratory measurements were 0.93, 0.91, and 0.74 for ^{226}Ra (^{238}U), ^{232}Th , and ^{40}K respectively. For the outdoor absorbed dose rate in air, the car-borne survey and the *in situ* measurements had a similar average value (44 nGy/hr) which was slightly below the average value (47 nGy/hr) of the laboratory measurements.

2) External annual effective dose recalculation

The effective external doses shown in Table 3 were evaluated taking into account the experimental value of the SF ($SF_{exp}=1.12$) of dwellings towards natural gamma-rays. This

Table 3. The External Annual Effective Dose, Calculated Using Shielding Factors Calculated in This Work and Reported in Our Previous Study [7]

Statistical parameters	External dose (mSv/yr)	
	E_{ext} ($SF_{exp}=1.12$)	E_{ext} ($SF=1.4$) [7]
Range	0.16–0.55	0.17–0.60
AM±SD	0.29±0.09	0.33±0.03
GM±GSD	0.27±1.34	0.32±1.34
Median	0.27	0.31
No. of dwellings	24	205

SF, shielding factor; AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation.

Table 4. Indoor Concentrations of Radon, Thoron, and Thoron Progeny

	Min	Max	AM±SD	GM±GSD	Median	No. of dwellings
Radon concentration (Bq/m ³)	88	282	133±39	128±1	125	46
Thoron concentration (Bq/m ³)	4	383	93±76	70±2	69	36
Thoron progeny concentration (Bq/m ³)	1	19	6±4	4±2	4	46

AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation.

Table 5. Inhalation Dose Calculated Using UNSCEAR 2000 (9 and 40 nSv/Bq·hr/m³) and ICRP 137 (16.8 and 107 nSv/Bq·hr/m³) Dose Conversion Factors for Radon and Thoron

Inhalation dose (mSv/yr)	UNSCEAR 2000			ICRP 137		
	Min	Max	Average	Min	Max	Average
E_{RIP} (radon inhalation dose)	1.74	5.58	2.63±0.77	3.18	10.21	4.82
E_{TIP} (thoron inhalation dose)	0.26	4.05	1.32±0.88	0.62	10.74	3.43
Total inhalation dose	1.96	9.63	3.95±1.65	3.80	20.94	8.22

UNSCEAR, United Nations Scientific Committee on the effects of Atomic Radiation; ICRP, International Commission on Radiological Protection; E_{RIP} , radon progeny inhalation dose; E_{TIP} , thoron progeny inhalation dose.

value was calculated from the ratio between the internal dose rate and the external dose rate, illustrated in Fig. 3. The external annual effective dose is 42% lower than the worldwide average value (0.5 mSv/yr).

2. Internal Exposure Due to Radon, Thoron, and Thoron Progeny

Indoor radon, thoron, and thoron progeny concentrations from our previous study [8] are summarized in Table 4. For radon, the activity concentrations range from 88 to 282 Bq/m³ with an arithmetic mean of 133 ± 39 Bq/m³ and a geometric mean of 128 ± 1 Bq/m³. For thoron, the concentrations ranged from 4 to 383 Bq/m³ with an arithmetic mean of 93 ± 76 Bq/m³ and a geometric mean of 70 ± 2 Bq/m³. Finally, concentrations

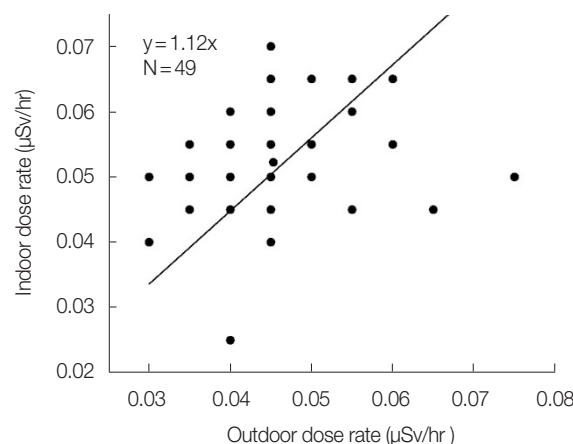


Fig. 3. Ratio of indoor to outdoor dose rates (µSv/hr) in the study area. N is the number of indoor and outdoor dose rate measurements.

of thoron progeny ranged from 1 to 19 Bq/m³ with an arithmetic mean of 6 ± 4 Bq/m³ and a geometric mean of 4 ± 2 Bq/m³. Table 5 displays the inhalation doses received from radon progeny and thoron progeny based on their corresponding measured activity concentrations and Equations (7) and (8), respectively. When using the UNSCEAR 2000 dose conversion factors, the yearly inhalation dose for radon and its progeny ranged from 1.74 to 5.58 mSv/yr with a mean value of 2.63 ± 0.77 mSv/yr, while for thoron and its progeny, the inhalation dose ranged from 0.26 to 4.05 mSv/yr with a mean value of 1.32 ± 0.88 mSv/yr. The total inhalation dose due to radon, thoron, and their progenies ranges from 1.96 to 9.63 mSv/yr with an arithmetic mean of 3.95 ± 1.65 mSv/yr. Different values were obtained when using the ICRP 137 conversion factors. These ranged from 3.18 to 10.21 mSv/yr, with a mean value of 4.82 mSv/yr for radon and its progeny and from 0.62 to 10.74 mSv/yr, with a mean value of 3.43 mSv/yr for thoron and its progeny. The mean total inhalation dose due to radon, thoron, and their progenies was calculated to be 8.22 mSv/yr, which is more than double the value calculated using the UNSCEAR factors. This highlights that is important to follow the future trends of international organizations in what values they use and to carefully consider what values are most appropriate for conducting effective risk assessments. However, regardless of which set of dose conversion factors are used, the inhalation dose calculated in this work is relatively high when compared to the world average value of 1.26 mSv/yr.

3. Excess Lung Cancer Risk Estimates

From the measured indoor radon concentrations (Table 4), the *ECR* was estimated for the population residing in the study area, using the risk factors (Table 1) recommended by the US EPA, UNSCEAR, and ICRP. The results obtained are

Table 6. Estimated Excess Lung Cancer Deaths per MPY Using the Recommended Risk Factors (per WLM) of Different International Agencies

Statistical parameters	Radon concentration (Bq/m ³)	Estimated excess lung cancer deaths per MPY		
		US EPA	UNSCEAR	ICRP
Minimum	88	41–143	54–161	89
Maximum	282	132–458	172–515	286
Average	133	62–216	81–243	135
Median	125	58–203	76–228	127

MPY, million person per year; WLM, working level month; US EPA, U.S. Environmental Protection Agency; UNSCEAR, United Nations Scientific Committee on the effects of Atomic Radiation; ICRP, International Commission on Radiological Protection.

presented in Table 6. From these results, the calculated *ECR* values at all selected houses are well above the world average values of 25 to 87 excess deaths per MPY, 32 to 97 excess deaths per MPY, and 54 excess deaths per MPY reported by the US EPA, UNSCEAR [1] and ICRP [28] respectively.

Conclusion

Public exposure to natural radiation was studied in Betare-Oya, a gold mining area in Eastern Cameroon. By using the activity concentrations of ²³⁸U, ²³²Th, and ⁴⁰K (Bq/kg) in soil obtained in previous studies, the outdoor absorbed gamma dose rates in air were estimated via a car-borne survey, *in situ* measurements, and conventional laboratory measurements of soil samples. The outdoor absorbed dose rates in air obtained from direct (i.e., the car-borne and *in situ*) measurements (44 nGy/hr) agreed well with that obtained via laboratory measurements (47 nGy/hr). The effective external doses were calculated based on the experimentally determined value of the *SF* ($SF_{exp} = 1.12$) of the dwellings. The resulting external effective dose (0.29 ± 0.09 mSv/yr) is similar to that of our previous study (0.33 ± 0.03 mSv/yr) calculated using a different *SF* ($SF = 1.4$). Thus, radioactivity levels in the surveyed areas are within normal global levels. On the other hand, inhalation doses due to radon, thoron, and their progenies, and *ECRs* were determined from the radon and the thoron activity concentrations measured in previous work. From these calculations, the total annual inhalation dose was estimated to be 3.95 ± 1.65 mSv/yr, which is higher than the world average value of 1.26 mSv/yr. Additionally, the *ECR* for the area studied is about 60% higher than the world average. Therefore, residents in the vicinity of Betare-Oya gold mining areas have a high level of risk from indoor radon. Thus, it would be desirable to educate members of the public about the harmful effects of radon exposure and to consider implementing remedial actions to protect residents against radon and its progenies.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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Ethical Statement

This article does not contain any studies with human participants or animals performed by any of the authors.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author Contribution

Conceptualization: Ndjana Nkoulou II JE. Methodology: Ndjana Nkoulou II JE. Formal analysis: Ndjana Nkoulou II JE, Ngoa Engola L, Dallou GB. Funding acquisition: Saïdou, Hosoda M, Kwato Ndjock MG, Tokonami S. Project administration: Saïdou, Hosoda M, Kwato Ndjock MG, Tokonami S. Visualization: Saïdou, Hosoda M, Kwato Ndjock MG, Tokonami S. Writing - original draft: Ndjana Nkoulou II JE. Writing - review and editing: Saïdou, Ngoa Engola L. Approval of final manuscript: all authors.

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