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From Radon and Thoron Measurements, Inhalation Dose Assessment to National Regulation and Radon Action Plan in Cameroon

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ABSTRACT

Background: The current study reports measurements of activity concentrations of radon (^{222}Rn) and thoron (^{220}Rn) in dwellings, followed by inhalation dose assessment of the public, and then by the development of regulation and the national radon action plan (NRAP) in Cameroon.

Materials and Methods: Radon, thoron, and thoron progeny measurements were carried out from 2014 to 2017 using radon-thoron discriminative detectors (commercially RADUET) in 450 dwellings and thoron progeny monitors in 350 dwellings. From 2019 to 2020, radon track detectors (commercially RADTRAK) were deployed in 1,400 dwellings. It was found that activity concentrations of radon range in 1,850 houses from 10 to 2,620 Bq/m^3 with a geometric mean of 76 Bq/m^3.

Results and Discussion: Activity concentrations of thoron range from 20 to 700 Bq/m^3 with a geometric mean of 107 Bq/m^3. Thoron equilibrium factor ranges from 0.01 to 0.6, with an arithmetic mean of 0.09 that is higher than the default value of 0.02 given by UNSCEAR. On average, 49%, 9%, and 2% of all surveyed houses have radon concentrations above 100, 200, and 300 Bq/m^3, respectively. The average contribution of thoron to the inhalation dose due to radon and thoron exposure is about 40%. Thus, thoron cannot be neglected in dose assessment to avoid biased results in radio-epidemiological studies. Only radon was considered in the drafted regulation and in the NRAP adopted in October 2020. Reference levels of 300 Bq/m^3 and 1,000 Bq/m^3 were recommended for dwellings and workplaces.

Conclusion: Priority actions for the coming years include the following: radon risk mapping, promotion of a protection policy against radon in buildings, integration of the radon prevention and mitigation into the training of construction specialists, mitigation of dwellings and workplaces with high radon levels, increased public awareness of the health risks associated with radon, and development of programs on the scientific and technical aspects.

Keywords: Radon, Thoron, Inhalation Dose, Reference Level, Radon Regulation, Radon Action Plan

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Introduction

Radon and thoron are ubiquitous in the air at ground level and are significant contributors to the average dose from natural background sources of radiation. In homes, underground mines, and other places where radon and thoron may be present and where ventilation may be limited, the levels of these radionuclides and their decay products can accumulate to high levels. Soils and rocks are often the main sources of radon [1]. Within the International Atomic Energy Agency (IAEA) BSS GSR, Part 3 [2], the government shall provide information on levels of radon indoors and the associated health risks and, if appropriate, shall establish and implement an action plan for controlling public exposure due to radon indoors.

The government shall ensure that an action plan is established comprising coordinated actions to reduce activity concentrations of radon in existing buildings and in future buildings where activity concentrations of radon that are of concern for public health are identified on the basis of the information gathered. It includes establishing an appropriate reference level for radon for dwellings and other buildings with high occupancy factors for members of the public, with account taken of the prevailing social and economic circumstances, which generally will not exceed an annual average activity concentration due to radon of 300 Bq/m^3 [2].

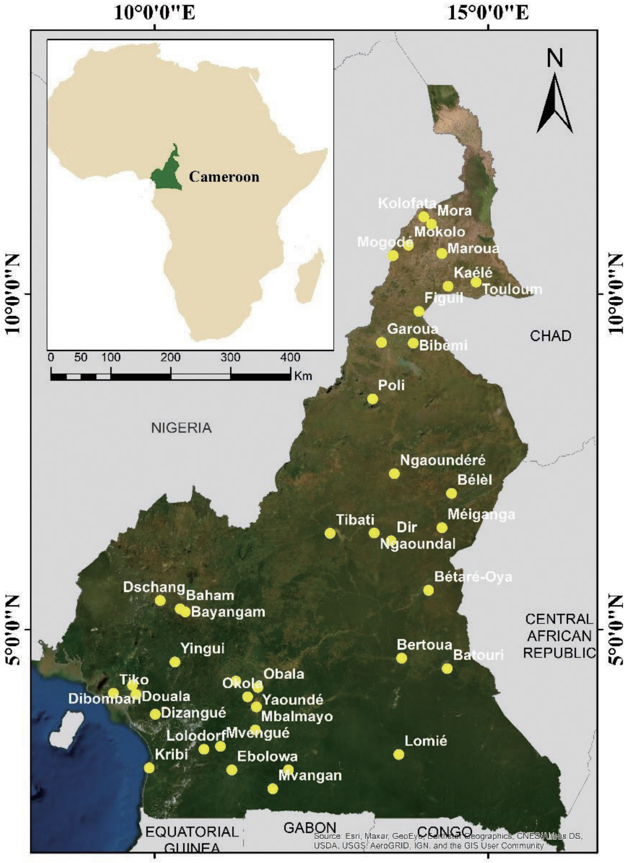
Few surveys of measuring thoron in dwellings are available worldwide and very few data are available from Africa. Salupeto-Dembo et al. [3] reported radon and thoron radiation exposure in the Angolan population living in adobe houses. Chege et al. [4] studied radon and thoron in earthen houses in rural Kenya. Since 2012, indoor radon measurements have been conducted in Cameroon first by measuring radon using the electret ionization chambers (EIC) in about 500 dwellings of some ore-bearing areas [5–7], then by discriminatively measuring radon and thoron in 450 dwellings using RADUET detectors in mining and ore-bearing areas of Cameroon [8–14]. The collected data in Cameroon helped to build a Technical Cooperation (TC) Project with IAEA called, "Establishing a national radon plan for controlling public exposure due to radon indoors." A total of 1,400 RADTRAK detectors were deployed collected and analyzed in the whole country. The results of the radon campaign in Cameroon and the corresponding effective dose assessment showing the importance to put in place radon regulations and a national radon plan will be presented. The progress of the regulation of radon and the implementation of the national radon plan will also be tackled.

Materials and Methods

1. Study Areas

Cameroon is a country located between Central and West Africa. It is bordered by Nigeria to the west and north; Chad to the northeast; the Central African Republic to the east; and Equatorial Guinea, Gabon, and the Republic of the Congo to the south. Cameroon's coastline lies on the Bight of Biafra, part of the Gulf of Guinea and the Atlantic Ocean. Both geographically and historically it belongs to West Africa. The country is sometimes referred to as West Africa and other times as Central Africa due to its strategic position at the crossroads between West and Central Africa. Cameroon is home to over 250 native languages spoken by nearly 25 million people. Cameroon has two official languages: French and English. It is extended on 475,000 km^2 and has 10 regions as shown in Fig. 1.

The country is often referred to as "Africa in miniature" for its rich geological and cultural diversity. Natural landscapes include beaches, deserts, mountains, rainforests, and savan-



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Fig. 1. The map of Cameroon showing all localities where radon was measured since 2012.

nahs. The highest point at 4,100 m is Mount Cameroon in the Southwest Region of the country, and the largest cities in terms of populations are Douala on the Wouri River, its economic capital and main seaport, Yaoundé, its political capital, and Garoua.

In the whole country, 1,850 dwellings were radon-surveyed in the whole country. Most of these houses were built using a mixture of cement, sand, and soil. Building materials mainly consisted of soil in rural areas where 90% of measurements were done. The ratio of the surveyed dwellings to the total dwellings ranges between 5% and 10%. About 50% of the surveyed dwellings in North and South regions are located in the uranium-bearing areas, while 50% of surveyed houses in the Adamawa and East regions are located in the bauxite, gold, cobalt, and nickel-bearing areas. At least 80% of the surveyed houses in the Center, Far North, and Littoral regions are located in normal areas. About 30% of surveyed dwellings in the West region belong to the bauxite-bearing areas.

2. RADUET Detectors

Indoor radon (half-life, 3.82 d) and thoron (half-life, 55.4 s) concentrations were measured simultaneously using a passive-type detector, namely, RADUET (developed at the National Institute of Radiological Sciences in Japan) [15]. RADUET detectors consist of two diffusion chambers (low and high diffusion chambers) with different air-exchange rates [16]. In each chamber, the CR-39 detector is fixed to detect the track of alpha particles. The high diffusion chamber used for the measurement of both radon and thoron contains six holes of 6 mm diameter opened in the chamber side wall and covered with an electro-conductive sponge to prevent radon and thoron progeny from easily going into the chamber [17]. That used for the measurement of radon only has a solid screw cap, with air entering the chamber through the cap thread. This provided sufficient time for the thoron to decay before gaining access to the detector. For a two-month exposure time, the lower detection limits of RADUET were about 10 Bq/m^3 for radon and 20 Bq/m^3 for thoron.

The radon and thoron calibration chambers at the Institute of Radiation Emergency Medicine, Hirosaki University, Japan, are composed of four parts: a source unit, a mixing chamber, an exposure chamber, and a monitoring unit [18]. To calibrate RADUET, natural rock samples and lantern mantles are used for radon and thoron sources, respectively. Radon gas generated from the source is transferred to the exposure chamber through the mixing chamber by an air pump. In the case of thoron gas, the mixing chamber was used for the exposure chamber because of its short half-life. It was found that radon and thoron concentrations could be controlled in the range of 200–1,000 Bq/m^3 and 3,500–30,000 Bq/m^3, respectively. The detectors were exposed to three different concentration levels (low, medium, and high concentrations) for radon and thoron. The concentrations of gas released by the sources are measured and monitored by the certified detectors; AlphaGuard for radon, Pylon AB-5, and RAD7 for thoron. These detectors are certified as reference devices by a Type-A laboratory.

3. Thoron Progeny Monitors

A deposition rate detector was used to measure the thoron progeny measurement [19]. This monitor consists of a CR-39 detector covered with an aluminized Mylar film of 71 mm thickness for the discrimination of high energy alpha particles, especially those emitted from ^{212}Po (8.78 MeV). The key radionuclides to determine the thoron progeny concentration are ^{212}Pb, ^{212}Bi, and ^{212}Po. More information on thoron progeny measurement using the CR-39 detector can be found in [19, 20].

To establish a calibration chamber for radon and thoron progenies at the Institute of Radiation Emergency Medicine, Hirosaki University in Japan, some aerosol generators were used with NaCl solution [21]. The aerosol generator is selected according to the aerosol size. Aerosols and the progenies were mixed in the mixing chamber to make radioactive aerosols, and then the radioactive aerosols were injected to the exposure chamber. The aerosol number concentration and the aerosol size distribution are measured by a scanning mobility particle sizer and a laser aerosol spectrometer, respectively.

With an emphasis on mining and high-potential mining areas, 450 dwellings were randomly selected for indoor radon and thoron measurements. Among them, 350 were considered for thoron progeny measurements. A triplet of monitors, including the low air-exchange rate chambers, high air-exchange rate chambers, and the deposition rate detector for radon, thoron, and thoron progeny, were deployed in each house. The detectors were suspended on the ceiling in the bedroom at a height of 1.5 to 2.0 m from the floor and 0.5 m from the wall. Measurements were done either in the rainy season or in the dry season depending on the study area. After a measurement period of two months, the detectors were collected and sent back to Hirosaki University in Japan for tracks evaluation.

The average radon and thoron concentrations are calculated as follows [22]:

$$\overline{C_{\mathrm{Rn}}} = \left(d_{\mathrm{L}} - \bar{b}\right)\frac{f_{\mathrm{Tn2}}}{t \times \left(f_{\mathrm{Rn1}} \times f_{\mathrm{Tn2}} - f_{\mathrm{Rn2}} \times f_{\mathrm{Tn1}}\right)} - \left(d_{\mathrm{H}} - \bar{b}\right)\frac{f_{\mathrm{Tn1}}}{t \times \left(f_{\mathrm{Rn1}} \times f_{\mathrm{Tn2}} - f_{\mathrm{Rn2}} \times f_{\mathrm{Tn1}}\right)} \quad (1)$$

$$\overline{C_{\mathrm{Tn}}} = \left(d_{\mathrm{H}} - \bar{b}\right)\frac{f_{\mathrm{Rn1}}}{t \times \left(f_{\mathrm{Rn1}} \times f_{\mathrm{Tn2}} - f_{\mathrm{Rn2}} \times f_{\mathrm{Tn1}}\right)} - \left(d_{\mathrm{L}} - \bar{b}\right)\frac{f_{\mathrm{Rn2}}}{t \times \left(f_{\mathrm{Rn1}} \times f_{\mathrm{Tn2}} - f_{\mathrm{Rn2}} \times f_{\mathrm{Tn1}}\right)} \quad (2)$$

where, d_{L} and d_{H} are alpha track densities (track/cm^2) for the low and high air-exchange rate chambers, respectively. f_{Rn1} and f_{Tn1} are the respective conversion factors from alpha track densities to radon and thoron activity concentration for the low exchange rate air chamber (track/cm^2/hr per Bq/m^3). f_{Rn2} and f_{Tn2} are the respective conversion factors from alpha track densities to radon and thoron activity concentration for the high exchange rate air chamber (track/cm^2/hr per Bq/m^3). t is the exposure time (hr) and $\bar{b}$ were the backgrounds of the alpha track density (tracks/cm^2) on the CR-39 detector. The lower detection limits were about 10 Bq/m^3 for radon and 20 Bq/m^3 for thoron.

Track densities (N_{TnP}) from the selective monitor for thoron decay products allow estimation of the equilibrium equivalent thoron concentration (EETC) from the following equation:

$$N_{TnP} = EETC \times F_{TnP} \times T + N_{B2} \quad (3)$$

where N_{B2} is the background track density of CR-39 in the thoron progeny deposition detectors, T is the exposure time, and F_{TnP} is the conversion factor for the thoron progeny deposition detector. From the results of a field survey [19] and the chemical etching conditions, the valuee of F_{TnP} was 6.9×10^{-2} tracks/cm^2 per Bq/m^3/hr. The detection limit of EETC was less than 0.01 Bq/m^3 for a measurement period of about 6 months.

The equilibrium factor for thoron was calculated for individual dwellings as follows:

$$F = \frac{EETC}{C_{Tn}} \quad (4)$$

where *EETC* is thoron progeny concentration and C_{Tn} is thoron concentration both in Bq/m^3.

One year after, radon, thoron, and thoron progeny measurements were performed using RADUET and thoron progeny monitors, only radon was now considered using RADTRAK detectors.

4. RADTRAK Detectors

Several 1,400 RADTRAK detectors were randomly deployed in dwellings of eight regions of the country with an emphasis on mining and high-potential mining areas. They were collected after a two-month exposure time and sent back to Radonova Laboratories for analysis in Uppsala, Sweden. The measurement is performed following the standard ISO 11665-4 [23]. The detector container is manufactured from electrically conducting plastic. Through a small slit (filter), radon gas enters the detector. The track-detecting material (film) inside the detector is hit by alpha particles generated by the radon entering the container and the decay products formed from it. On the film, the alpha particles make small tracks, which are enlarged with chemical etching and later counted in a microscope to determine the radon exposure. The lowest detection limit for a measurement period of two months is 15 Bq/m^3. The arithmetic mean of radon activity concentration (Bq/m^3) is given as follows:

$$\bar{C} = \left(n_{\mathrm{g}} - \bar{n}_{\mathrm{b}}\right)\frac{1}{t \cdot S_{\mathrm{SSNTD}} \cdot F_{\mathrm{c}}} = \left(n_{\mathrm{g}} - \bar{n}_{\mathrm{b}}\right) \cdot \omega \quad (5)$$

$$\omega = \frac{1}{t \cdot S_{\mathrm{SSNTD}} \cdot F_{\mathrm{c}}} \quad (6)$$

where n_{g} is the number of tracks after exposure, $\bar{n}_{\mathrm{b}}$ is the mean number of tracks caused by the background radiation, t is the sampling duration, F_{c} is the calibration factor, ω is the correction factor linked to the calibration factor and the sampling duration, and S_{SSNTD} is the detector area used for counting the number of etched tracks in units of cm^2.

For the most accurate value, $\bar{n}_{\mathrm{b}}$ is determined experimentally by reading n detectors that have not been exposed to radon and have been processed under the same physicochemical and counting conditions. The value of $\bar{n}_{\mathrm{b}}$ may also be given by the manufacturer.

5. Inhalation Dose Assessment

Indoor inhalation doses were evaluated in this study on activity concentrations of radon and thoron progeny and dose conversion factors. As it is generally accepted that the risk of lung cancer comes from the decay products rather than the parents. Otherwise, because of its short half-life, thoron has an inhomogeneous spatial distribution, thoron concentrations were not taken into account for dose estimation. It was highlighted that thoron concentrations follow an exponential decrease from the wall of the house [24]. Thus, using thoron concentration with only one measurement in a dwelling for dose assessment may lead in these circumstances to large uncertainties in the results. Annual effective dose E (mSv/yr) due to inhalation of indoor radon and thoron was estimated as follows [25]:

$$E_{\mathrm{RnP}} = e_{\mathrm{Rn}} \times F_{\mathrm{eqRn}} \times C_{\mathrm{Rn}} \times F_{\mathrm{occ}} \times t \qquad (7)$$

$$E_{\mathrm{TnP}} = e_{\mathrm{TnP}} \times EETC \times F_{\mathrm{occ}} \times t \qquad (8)$$

where C_{Rn} and $EETC$ are activity concentrations of radon and thoron progeny, respectively. e_{Rn} and e_{TnP} are the inhalation dose conversion factors (9 and 40 nSv per Bq/m^3/hr) for radon and thoron progeny, respectively. F_{occ} is the occupancy factor (0.6) for the studied areas. F_{eqRn} is the equilibrium factors for radon (0.4) [25], t is the exposure time which was adjusted to one year and expressed in hours.

It should be noted that the conversion factor proposed by United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [25] has recently been called into question by the International Commission on Radiological Protection (ICRP) [26], which suggests a correction by a factor of two upward. In 2017, the ICRP published new, higher dose conversion factors for radon, which therefore increased the calculated radiation dose associated with exposure to radon in workplaces [27]. For the calculation of doses following the inhalation of radon and radon progeny in underground mines and buildings, in most circumstances, the ICRP recommends a dose coefficient of 3 mSv per mJ · hr/m^3 (approximately 10 mSv/WLM, where WLM is a working level month).

UNSCEAR, however, has confirmed in a report on lung cancer from exposure to radon in 2019 that the evidence reviewed by its experts is compatible with the available data in the committee's previous assessment of lung cancer risk due to radon [28]. Therefore, UNSCEAR concluded that there is no reason to change its established dose conversion factor and recommends the continued use of the dose conversion factor of 9 nSv per Bq · hr/m^3 Equilibrium equivalent concentration (EEC) of ^{222}Rn, which corresponds to 1.6 mSv per mJ · hr/m^3 for estimating radon exposure levels to a population. This new report was approved by the Fourth Committee of the United Nations General Assembly in October 2019.

Finally, the uncertainty in the dose conversion factor should be taken into consideration when assessing inhalation dose due to radon indoors.

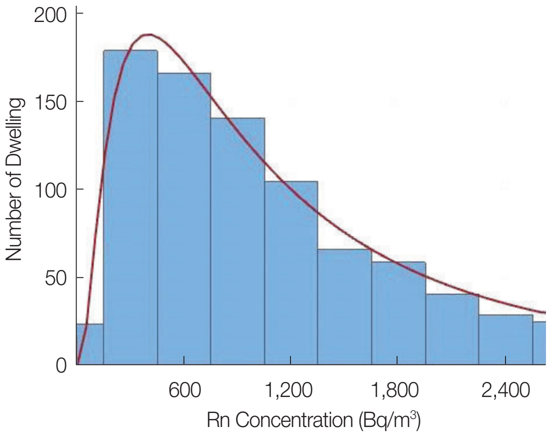


Fig. 2. Lognormal distribution of ^{222}Rn in 1,850 dwellings of eight regions of Cameroon.

Results and Discussion

1. Radon, Thoron and Thoron Progeny Concentrations

Radon, thoron, and thoron progeny were measured in 1,850, 450, and 350 dwellings, respectively. One should note that the study areas consist of inhabited mining and ore-bearing areas and non-mining or non-ore-bearing regions. Fig. 2 shows lognormal distribution of radon in 1,850 dwellings in eight regions of Cameroon. The corresponding geometric mean is 76 Bq/m^3. Table 1 displays radon, thoron, and thoron progeny concentrations ranging between 10–2,620 Bq/m^3, 20–700 Bq/m^3, and 0.4–36 Bq/m^3, respectively. The corresponding arithmetic means are 103 Bq/m^3, 107 Bq/m^3, and 6.8 Bq/m^3. It can be observed that the geometric and arithmetic means at the national scale are well above the world average value of 40 Bq/m^3 given by UNSCEAR [25]. On average 49%, 9%, and 2% of all surveyed houses have radon concentrations above 100, 200, and 300 Bq/m^3, respectively. These three values were used for comparison to better understand the exposure level of radon in the study areas. A national reference level of 100 Bq/m^3 is recommended by the World Health Organization. Wherever this is not possible, the chosen level should not exceed 300 Bq/m^3. It appears important to put in place radon regulations and the NRAP in Cameroon. Table 2 shows the percentage of houses having radon and thoron concentrations above some reference or specific levels in the regions of Cameroon. Various findings can be brought out. Thoron cannot be neglected when deal-

Table 1. Minimum, Maximum, and Mean Radon, Thoron and Thoron Progeny Concentrations in Eight of the Ten Regions of Cameroon

Region	Number of dwellings	Arithmetic mean (Bq/m^3)			Range (Bq/m^3)		
		Radon	Thoron	Thoron progeny	Radon	Thoron	Thoron progeny
Adamawa	300	133	-	-	30–540	-	-
Center	200	48	-	-	10–235	-	-
East	170	80	92	6	27–300	20–383	0.6–19
Far North	270	157	-	-	62–310	-	-
Littoral	240	95	80	4.6	10–436	20–246	1.5–13
North	220	48	94	6.4	10–2,260	24–238	4–9
North-West	-	-	-	-	-	-	-
South	250	113	160	10.3	23–2,620	20–700	0.4–36
South-West	-	-	-	-	-	-	-
West	200	140	-	-	30–530	-	-
Whole country		103	107	6.8	10–2,620	20–700	0.4–36

Table 2. Percentage of Houses Having Radon and Thoron Concentrations above Some Reference or Specific Levels in the Regions of Cameroon

Region	Percentage (%) of houses having radon above the reference levels (Bq/m^3)			Percentage (%) of houses having thoron above some specific levels (Bq/m^3)		
	≥100	≥200	≥300	≥100	≥200	≥300
Adamawa	58	14	5	-	-	-
Center	6	2	0	-	-	-
East	33	2	1	19	9	2
Far North	90	16	1	-	-	-
Littoral	33	1	1	32	3	0
North	20	3	3	43	2	1
North-West	-	-	-	-	-	-
South	47	2	1	56	33	15
South-West	-	-	-	-	-	-
West	72	13	3	-	-	-

ing with radon issue. Three regions (Adamawa, Far North, and West) have on average radon concentrations higher than those of other regions. They have corresponding radon concentrations of (58%, 14%, 5%), (90%, 16%, 1%), and (72%, 13,%, 3%) in houses that are higher than the reference levels (100 Bq/m^3, 200 Bq/m^3, and 300 Bq/m^3). The city of Ngaoundéré, capital of the Adamawa Region appears as the most radon-exposed area with 28% of houses having radon concentrations above the reference level of 300 Bq/m^3. This city can be classified as a radon-prone area [29].

The highest radon concentration of 2,620 Bq/m^3 was found in a dwelling of the city of Ebolowa, the capital of the South Region [30]. This high radon concentration could be explained by the geology of the area and the type of dwelling, which is not naturally ventilated sufficiently. Additional field works are currently carried out in the whole country to measure geogenic radon, indoor radon, thoron, and their progeny using new techniques ever been used during the previous studies in Cameroon. Most radon-prone areas of the country will be located in the coming years. The NRAP developed in response to this radon survey defined mitigation actions to be applied to the high radon dwellings to ensure the radiological protection of people.

Thoron equilibrium factors range between 0.01–0.6 with the arithmetic mean of 0.09 higher than the default value of 0.02 given by UNSCEAR [1]. Determining the equilibrium factor is useful for assessing inhalation dose. One should note that only thoron equilibrium factors were calculated from experimental data while equilibrium factor of radon 0.4 given by UNSCEAR [25] was used. However radon progeny will be measured in dwellings in the near future to determine experimentally the corresponding equilibrium factor ensuring more reliable inhalation dose assessment [14].

2. Inhalation Dose

As displayed in Table 3, the annual effective dose due to inhalation of radon and thoron exposure indoors ranges between 0.06–50 mSv and 0.08–8.0 mSv. The mean value for radon at the national level is 1.9 mSv higher than the world average value of 1.2 mSv ranging between 0.2 and 10 mSv given by UNSCEAR [25]. The mean value of inhalation dose due to thoron exposure indoors is 1.75 mSv. The contribution of thoron to inhalation dose due to radon and thoron exposure ranges between 12%–67%, 3%–80%, 7%–70%, and 7%–60% in the North, South, East, and Littoral regions, respectively. The corresponding average values are 49%, 53%, 31%, and 26%. It highlights the importance to consider thoron in inhalation dose assessment of radon to avoid biased results in epidemiological studies. This result contributes to bringing out the urgent need to regulate thoron exposure at the international level.

Table 3. Inhalation Dose due to Radon, Thoron, and Thoron Progenies Indoors in the ten Regions of Cameroon

Region	Mean annual effective dose (mSv)		Range (mSv)	
	^{222}Rn	^{220}Rn	^{222}Rn	^{220}Rn
Adamawa	2.5	-	0.8–10.2	-
Center	0.9	-	0.06–4.5	-
East	1.5	2	0.5–5.7	0.13–4.0
Far North	3	-	1.2–4.0	-
Littoral	1.8	1	0.05–8.2	0.3–3.0
North	0.9	1.8	0.07–43	0.34–6.2
North-West[a]	-	-	-	-
South	2.1	2.2	0.4–50	0.08–8.0
South-West[a]	-	-	-	-
West	2.6	-	0.6–10	-

[a] Except the North-West and South-West regions where measurements are ongoing.

3. Radon Regulation and NRAP

The collected data on radon by using the EICs and the RADUET detectors helped to build a TC Project with IAEA called, “Establishing a national radon plan for controlling public exposure due to radon indoors,” implemented within the framework of IAEA TC cycle 2018–2019. Three actions (training, equipment, and expert visit) were fully implemented. In terms of the equipment, 1,500 radon track detectors were delivered. A radon calibration system was provided to allow independent and reliable radon measurements. Equipment for radon measurements in soil and in-situ gamma spectrometer was also provided for radon risk mapping. Moreover, 20 integral radon monitors were delivered to allow for long-term radon measurements at workplaces and in dwellings. Regulation on radon was drafted from 2019–2020 and the process to adopt it is ongoing. The NRAP was validated

Table 4. Institutions Involved in the Implementation of the National Radon Action Plan and their Missions

Stakeholder	Role
National Radiation Protection Agency	- Exploiting collected data on radon to develop or strengthen regulation of public and workers' exposures to radon. - Responsible for the implementation of Radon Action Plan, coordination of radon risk communication and regulatory control of radon at workplaces.
Institute of Geological and Mining Research	- Radon risk mapping. - Playing a key role in all technical aspects on radon issues.
Ministry of Housing and Urban Development	- Developing building codes and building regulations, requiring radon protection measures in all new buildings under construction. The organized groups of building professionals will be associated.
Ministry of Labour and Social Security	- Regulating the working conditions standards and health risks at workplaces as well as enforcement of these regulations.
Ministry of Public Health Public	- Implementing and enforcing regulations on radon in workplaces. - Radon risk communication. - Health risks mitigation. - Regulatory control of workplaces.
Ministry of Higher Education	- Developing curricula of higher training schools of civil engineering by taking account of radon mitigation in buildings.
Ministry of Decentralization and Local Development	- Facilitating indoor radon measurements in the cities in collaboration with the city councils. - Applying standards of construction by building construction specialists taking account of radon protection.
Ministry of Public Works	- Approving public building construction taking into consideration radon issues.
Ministry of Communication	- Radon risk communication.
Ministry of Environment and Sustainable Development	- Intervening in radon measurements in the environment, particularly during environmental impact studies of industrial unit installation projects.

during a national workshop in October 2020 involving all the national stakeholders.

To efficiently develop and prepare for the implementation of the young national radon action plan and mitigate high radon levels in houses and workplaces, capacity building on radon risk communication, radon mitigation, and prevention, and radon regulation should be taken into account within the framework of a follow-up project called: "Strengthening national radon action plan (NRAP) to mitigate public exposure to radon in dwellings and at workplaces in Cameroon", during 2022–2023 IAEA TC Cycle. Table 4 shows the main stakeholders and their roles in the implementation of the NRAP in Cameroon.

Conclusion

Radon has been measured in more than 2,300 houses at the national scale since 2012. Collected data brought out the importance to develop radon regulation and NRAP. Regulation on radon was drafted and the process to adopt it is ongoing. The NRAP was validated during a national workshop involving all the national stakeholders. The next step is to make operational the national radon plan and radon regulation by emphasizing on the following major objectives: radon risk mapping (dwellings, workplaces, and soil), promotion of a protection policy against radon in buildings, integration of radon prevention and mitigation into the training of construction specialists, mitigation of dwellings and workplaces with high radon levels, improving public awareness to health risks caused by radon, and development of programs on the scientific and technical aspects.

At the international level, there is a requirement to take into consideration thoron exposure in the regulation of radon. Thus thoron reference levels should be defined.

Conflict of Interest

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

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Author Contributions

Conceptualization: S. Methodology: S, ST, MH. Formal analysis: S, ST, MH. Funding acquisition: S, ST, AS, JVH, OG, EGOM. Project administration: S, ST, AS, OG, EGOM. Visualization: S. Writing - original draft: S. Writing - review and editing: S, ST, MH. Approval of final manuscript: all authors.

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