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Review Article

Radon Exposure Measurement Technique: A Literature Review

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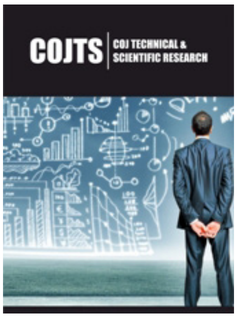

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Summary

The health impact of the exposure of populations to radon-222 and 220 is no longer to be demonstrated when they are exposed to high concentrations of volumetric activities. The measurement of radon requires specific techniques. The aim of this study was to identify the measurement methods allowing the identification and measurement of radon-222 and thoron-220 inside and outside homes and in establishments receiving the public. A systematic review of the literature was conducted. We identified scientific articles that addressed the issue of radon-222 and 220 exposure. The searches included all worldwide literature from 2000 to 2021. A total of three hundred and seventy (370) articles were collected from the search engines www.semanticscholar.org. The criteria were defined and applied to select relevant articles for the review. Then, a specific selection was made to eliminate articles with similarities in terms of methodology and the objective of the measurement in the different countries of publication. Finally, a global analysis of all the articles retained after the first selection was performed. The data analysis was performed with Excel. For this review, three hundred and eleven (311) publications were identified and included in our selection criteria, i.e., 84%. 0.3% of these publications were written in French. 43 specific and exclusively distinct articles were identified in the 311 pre-selected articles. The measurement of radon had become an issue in the scientific world since the 2010s. The present review showed that four sources of natural exposure are possible for humans. These are: water, soil, indoor air in rooms and public buildings and outdoor air. From this review, three techniques for measuring the exposure of radon-222 and thoron-220 were identified. These are: Solid Nuclear Trace Detectors (SNTD), gamma & alpha spectrometry and Liquid Scintillation Technique (LSC). 8 detectors based on these techniques have been identified in this review and have a representativeness greater than or equal to 4%. The Columbia Resin-39 (CR-39) solid-state nuclear trace detector is the most representative (32%) including the African context of radon-222 measurement in premises. The observation-based evaluation of the three measurement techniques showed that NSTDs are the most recommended for passive measurement of indoor radon. Liquid scintillators are the most recommended for the active measurement of radon in drinking water. However, the spectrometry technique (HpGe, Alphaguard) has also been shown to be effective in the active measurement of radon in liquid compartments. For the quantitative and qualitative analysis of radionuclides present in a soil sample, including radon and its solid progeny, gamma or alpha spectrometry remains the technique of choice. The measurement of radon-222 and thoron-220 requires a precise technique adapted to the measurement environment (indoor, outdoor, water, soil and food). The present review has allowed to note an absence of scientific research on the subject of exposure due to radon-222 in Benin. It allowed to identify the three representative techniques in formation of the measurement compartment.

Introduction

Radon 222 and thoron 220, with a half-life of 3.82 days and 55.6s, are radioactive gases resulting from the radioactive decay of uranium-238 and thorium-232 in the earth's crust. Specifically, radon and thoron are inert radioactive gases and react little with the tissues of the human body. They have a low solubility in human tissues. The radiotoxic consequences of exposure to these isotopes are inflicted on their short-lived progeny which are solid inhalable particles [1]. After inhalation, they are deposited in the lung alveoli and interact with the gas exchange tissues during their physical life cycles [2,3]. Studies have shown that chronic exposure to radon and its decay products is the second leading cause of lung cancer after smoking [4,5]. More than half of the average annual dose from background (natural) radiation is due to radon and its progeny, which, due to electrostatic forces, can attach to aerosols and plate on the skin significantly increasing the potential dose delivered to this organ [6]. According to UNSCEAR, the average annual dose due to exposure to natural sources of radiation, including radon, in the world is 2.4mSv [7]. Thus, for the purpose of radiological protection, the International Atomic Energy Agency (IAEA), based on ICRP publications 103 and 115, has set the regulatory limit of atmospheric radon concentration in homes at 300Bq/m^3, which corresponds to an annual dose of about 10mSv [8,9]. Indeed, radon-222 is easier to measure because of its half-life. The first scientific studies and measurement techniques focused on radon-222 [4,5]. By the 2010s, the determination of the contribution of each isotope has become a reality in the scientific world [4]. For example, Yuji Yamada et al. performed the separate measurement between radon and thoron in GANSU province in China in 2014 using the CR-39 type Solid Nuclear Trace Detector (SNTD) [6]. The requirement No. 50 of IAEA safety standard GSR Part 3, requires each state to establish radon levels in the premises as well as a national remediation plan [10]. Thus, in accordance with IAEA guidelines, France has established several standards on radon metrology according to the measurement compartments (water, air, soil, dwellings) [11,12]. Benin has adopted the law 2017-29 of March 15, 2018 on radiological safety and nuclear security in the Republic of Benin, which defines the legislative requirements for radiological protection. This law prescribes in its article n°12 that radiation protection is a national duty [13]. Thus, the National Authority for Radiological Safety and Radiation Protection (ANSR), through its decision n°073 of March 25, 2021 on the radiation protection of workers, has set a limit of 1000Bq/m^3 for the average annual radon activity concentration in the workplace [14]. These international and national dose constraints must be respected in Benin. In view of all this, and with regard to the national legislative and regulatory texts mentioned above, and with a view to determining the most suitable measurement technique for radon dosimetry in Benin, we have carried out the present literature review on radon 222 and thoron 220 measurement methods.

Methods

In order to conduct this literature review, we conducted a systematic search of publications related to radon measurement from 2000 to 2021 in search engines such as Google Scholar and scientific databases such as PubMed, Wiley, NCBI, IEEE Xplore, Scopus, Web of Science and Semantic scholar. Searches are performed in databases using the following phrases: “Radon exposure”, “radon measurement in the open air”, “radon measurement in homes”. Reference lists of all retrieved studies were also searched for relevant studies that may have been missed in the database search. The books cited in the study references were consulted and mined. By examining the titles and/or abstracts, the initial selection of articles was performed independently by the first author (F/A), and the last author (L/A) based on inclusion criteria. The criteria were: radon dosimetry, radon monitoring, factors influencing radon measurement, sources of radon exposure, and radon measurement method. In addition to these criteria, only English and French papers were selected for inclusion in the review. A third author supervised the selection process and in case of doubt, the data were discussed until an agreement was reached between the three parties. Based on the inclusion criteria, after selection, the articles were classified by topic.

Results

Evolution of scientific publications according to the year

Of a total of 370 publications collected, 59 articles were excluded from the study. Finally, 311 articles were included in this review (Figure 1). Analysis of this curve shows that the publication of articles related to radon exposure monitoring has evolved in a sawtooth fashion between 2000 and 2007. An increasing trend was observed between 2008 and 2015. This is justified on the one hand by the availability of radon measurement devices and on the other hand by the requirements of the International Commission on Radiological Protection (ICRP) on the problem of domestic and workplace radon exposure through its publication 103 in 2007 [8]. The decrease observed between 2015 and 2018 can be justified by a standardization of radon measurement methods. In order to make an in-depth analysis of the selected articles, the articles were divided by country and continent.

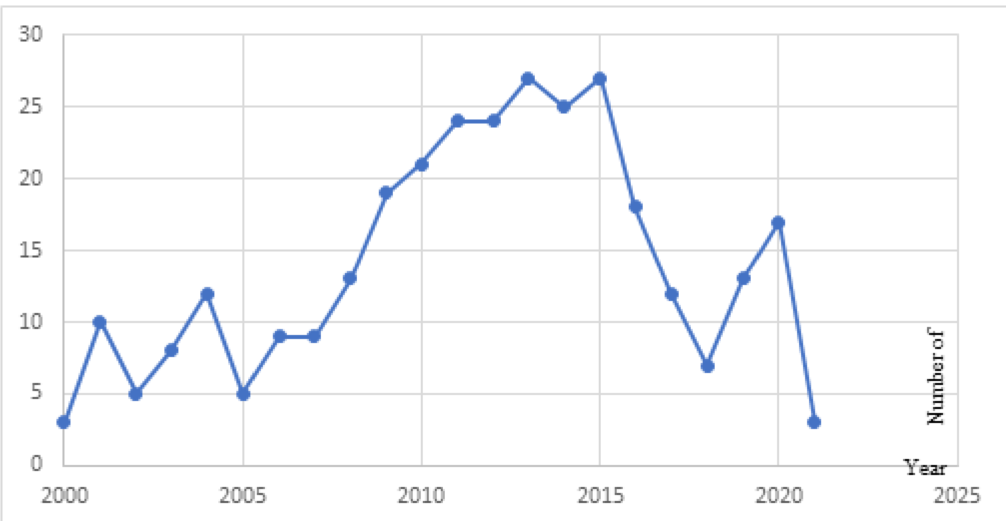

Figure 1: Distribution curve of article publications by year.

Distribution of publications by country and by continent

In order to identify the measurement methods leading to the identification and measurement of radon, we have scoured the world literature. The graph below shows the number of articles per country on each continent (Figure 2). From these graphical distributions by continent, we notice that our research theme has a strong literature review in terms of publication of articles. To this effect, we note a strong literature on the European and Asian continents. At the level of these countries, India, France and Japan have more articles on measurement methods (detectors) in the world with respectively 29, 21 and 20 articles. Ten countries have made more than ten publications from 2000 to 2021. These are France, Japan, Turkey, USA, Italy, Spain, China, India, Hungary and Serbia. Six (06) African countries have made publications on the problem of exposure due to radon-222 and thoron-220. They are Cameroon (9), Egypt (5), Tunisia (1), Nigeria (5), Kenya (1) and Madagascar (1), that is to say 22 publications (7.07%). The analysis of these articles allowed the identification of articles from each country with similarity in radon exposure sources. A total of 43 articles were selected. These articles showed their difference on the world scientific scene on the topic of radon exposure monitoring. We will use them in the following sub-sessions. By analyzing the different topics addressed in the selected articles, the rest of this literature review is organized in three sub-sessions namely: sources of exposure, radon measurement techniques and factors of influence of radon metrology.

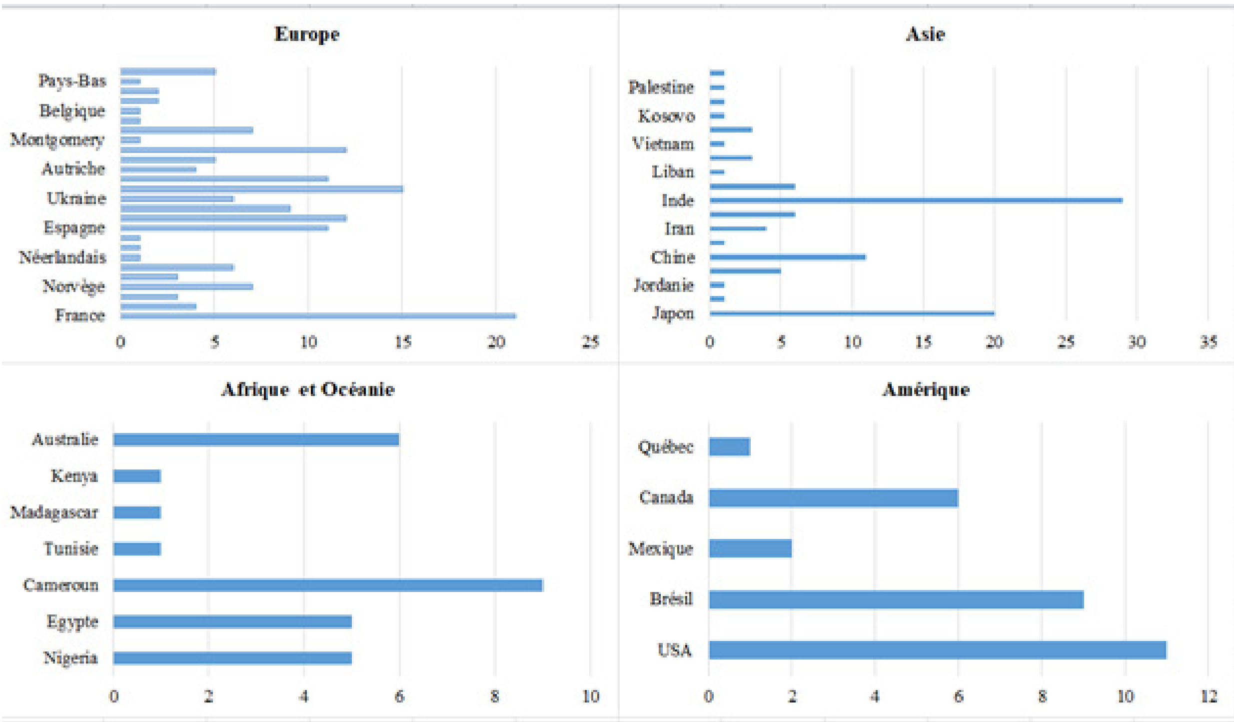

Figure 2: Distribution of articles by continent and by country of research.

Sources of Radon Exposure

Because radon is a naturally occurring radioactive gas, its sources of exposure are diverse and varied. By exploiting the frameworks of the different articles, the following sources of exposure were identified. These are: drinking water, indoor air, outdoor air and soil. The table below shows the statistics of the studies on radon measurement in the different compartments (Table 1).

Table 1: Summary of sources of exposure to radon-222 and thoron-220.

Sources of Exposure	Referenced Articles	Number of Distinct Articles Referenced out of 311 Articles	The Types of Detectors Used in these Articles
Water: - Drinking tap water ; - Well ; - River ; -Underground.	1. Supriya Rani et al. 2021. Assessment of radiological risk to the public from radon in water in the Barnala district, Punjab, Inde. INDE. 2. C G Poojitha et al. 2020. Assessment of radon and thoron exhalation from soils and dissolved radon in groundwater in the vicinity of a high granitic hill, chikkaballapur district , karnataka, inde. INDE. 3. Jamilu Tijjani Baraya et al. 2020. Measurement of radon-222 concentration levels in brands of drinking water sachets produced in dutsin ma local government area (lga) of katsina state, Nigeria; 4. Khalid Abdulaziz Aleissa and al. 2012. Measurement of radon levels in groundwater supplies of riyadh with liquid scintillation counter and the associated radiation dose. saudi arabia. 5. Hakan Yakut and al. 2013. Measurement of 222Rn concentration in drinking water in sakarya, Turkey. Turkey. 6. M. Erdogan and al. 2013. Determination of radon concentration levels in well water in konya, Turkey. Turkey. 7. U. Akar Tarim and al. 2011. Evaluation of radon concentration in well and tap waters in bursa, Turkey. Turkey. 8. William C. Burnett, Henrieta Dulaiova and al. 2003. Estimation of groundwater inflow dynamics in the coastal zone by continuous radon-222 measurements. USA.	8	RAD7, Smart RnDuo or LSC (Liquid Scintillation Counter) monitor
Premises: - Dwellings; - Elementary schools ; - Churches ; - Mosques; - Building materials.	9. Tetsuya Sanada. 2021. Measurement of Indoor Thoron Gas Concentrations Using a Radon-Thoron Discriminative Passive Type Monitor: Nationwide Survey in Japan. JAPON. 10. Takoukam Soh Serge Didier et al. 2019. Simultaneous measurements of indoor radon and thoron and inhalation dose assessment in Douala City, Cameroon. CAMEROON. 11. M.F. Máduar and al. 2016. Assessment of external gamma exposure and radon levels in a dwelling constructed with phosphogypsum plates. BRAZIL. DOI : 10.1016/j.jhazmat.2011.03.019. 12. Abd-Elmoniem A. Elzain and al. 2014. Radon exhalation rates from some building materials used in Sudan. SUDAN. 13. R. I. Mohamed et al. 2013. Measurements of radon gas concentrations in dwellings of al-madinah al-munawarah province in saudi arabia. SAUDI ARABIA ; 14. Constantin Cosma and al. 2012. Soil and building material as main sources of indoor radon in Baita-Stei radon prone area. Romania. 15. B. Kucukomeroglu et al. 2012. A study of environmental radioactivity in Samsun province, Turkey. TURQUIE ; 16. R. Ciolini. 2010. Indoor radon concentration in geothermal areas of central Italy. Italy. 17. N. Celik and al. 2008. Determination of indoor radon and soil radioactivity levels in Giresun, Turkey. Turkey. 18. Kamal Hadad and al. 2007. Indoor radon monitoring in Northern Iran using passive and active measurements. IRAN. 19. Krisztian Hamori and al. 2006. Evaluation of indoor radon measurements in Hungary. HUNGARY. 20. Claus E. Anderson and al. 2001. Mapping indoor radon-222 in Denmark: design and test of the statistical model used in the second nationwide survey. DENMARK. 21. Aleksandar Birovljev & all. 2001. Retrospective assessment of historic radon concentrations in Norwegian dwellings by measuring glass implanted Po-210 an international field intercomparison. NORWAY.	13	CR-39

Soil: - Uranium, Manganese and Phosphate mining sites.	22. Deborah Tolulope Esan. 2020. Determination of Residential Soil Gas Radon Risk Indices Over the Lithological Units of a Southwestern Nigeria University. NIGERIA. 23. Darren Huxtable. 2016. Measuring radon-222 in soil gas with high spatial and temporal resolution. UKRAINE. 24. V. Moreno and al. 2015. Soil radon dynamics in the Amer fault zone: An example of very high seasonal variations. ESPAIN. 25. M.A. Hilal and al. 2015. Investigation of some factors affecting on release of radon-222 from phosphogypsum waste associated with phosphate ore processing. EGYPT. 26. G. Cinelli and al. 2014. Soil gas radon assessment and development of a radon risk map in Bolsena, Central Italy. ITALY. 27. J. Mazur and K. Kozak. 2014. Complementary system for long term measurements of radon exhalation rate from soil. POLAND. 28. Rodrigue S Allodji and al. 2012. Assessment of uncertainty associated with measuring exposure to radon and decay products in the French uranium miners cohort. FRANCE. 29. R.M. Anjos and al. 2011. External gamma-ray dose rate and radon concentration in indoor environments covered with Brazilian granites. BRAZIL. 30. N. Kavasi and al. 2010. Effective dose of miners due to natural radioactivity in a manganese mine in hungary. HUNGARY. 31. Cameron E. Lawrence and al. 2008. Radon-222 exhalation from open ground on and around a uranium mine in the wet-dry tropics. AUSTRALIA. 32. Weihai Zhuo and al. 2008. Estimating the amount and distribution of radon flux density from the soil surface in China. CHINA. 33. Aud Venke Sundal and al. 2007. The influence of meteorological parameters on soil radon levels in permeable glacial sediments. NORWAY. 34. J. Swakon, K. Kozak et al. 2004. Radon concentration in soil gas around local disjunctive tectonic zones in the Krakow area. POLAND. 35. Mahmoud Kullab. 2002. Assessment of Radon-222 Concentrations in Buildinps, Building Materials, Water and Soil in Jordan. JORDAN.	14	HpGe detector, CR-39, AlphaGUARD PQ 2000Pro and LR-115 type II.
Outside air	36. YONGLING YUAN and al. 2021. Measurements of Rn-222, Rn-220 and Their Decay Products in the Environmental Air of the High Background Radiation Areas in Yangjiang, China. China. 37. M. Kümmel and al. 2014. Outdoor 222Rn-concentrations in Germany : part 2 former mining areas. Germany. 38. M. Kümmel and al. 2014. Outdoor 222Rn-concentrations in Germany e part 1 natural background Germany. 39. Jelena Mrdakovic Popic and al. 2011. Outdoor 220Rn, 222Rn and terrestrial gamma radiation levels: investigation study in the thorium rich Fen Complex, Norway. NORWAY. 40. N. Harley and al. 2010. Measurement of the indoor and outdoor 220rn (thoron) equilibrium factor: application to lung dose. USA. 41. Patrick Richon and al. 2004. Spatial and time variations of radon-222 concentration in the atmosphere of a dead-end horizontal tunnel France. 42. M.H. Magalhaes and al. 2002. Radon-222 in Brazil: an outline of indoor and outdoor measurements. Brazil. 43. Janja Vaupotic & all. 2000. Systematic indoor radon and gamma-ray measurements in slovenian schools. Slovenia	8	CR-39, LR-115 type II and HpGe-Detector

Drinking water as a source of radon exposure

Water has been identified by the scientific community as a source of radon exposure. In view of its importance in the diet of the population, the authors were interested in the quantitative evaluation of the volume concentration of radon in water. *Hakan Yakut* evaluated the concentration of radon-222 in drinking water in the city of SAKARYA in Turkey in 2013 [15]. Well water had an average concentration of 9.05Bq/l, thermal spring water was 13.78Bq/l and 5.41Bq/l for bottled water. The same study was performed by M. Erdogan et al. in 2013 in the city of KONYA in Turkey and showed lower values [16]. *U. Akar Tarim* col in 2011 performed the same study on tap and well water in Bursa city in Turkey. The concentration for well water ranged from 1.46 to 53.64Bq/l and for tap water from 0.91 to 12.58Bq/l [17]. These values are relatively higher than the national limit set by the Turkish state which is 11.1Bq/l. Khalid Abdulaziz Aleissa et al. evaluated the radon concentration in groundwater in Saudi Arabia in 2012 and proved that it represents a source of exposure to the population [18]. It should be noted that the different drinking water compartments are a source of exposure and it is necessary to do radon monitoring to determine the level of exposure of the population. The populations of Benin's cities, in particular those of mountainous cities, also use well, ground and tap water for their vital needs. It is necessary to evaluate the concentration of radon present in these drinking water sources.

Exposure to radon in the home

The inhabited premises constitute a source of exposure to radon. Several authors have learned their studies in the metrology of atmospheric radon concentration in dwellings. The analysis of the articles showed that the term "habitations" is subdivided into three major parts namely: bedrooms (domestic radon) and public accommodations such as schools, churches, mosques etc. *Kamal Hadad* in 2007 evaluated the volume activity of radon in dwellings in the cities of Lahijan, Ardabil, Sar-Ein and Namin in Iran [19]. The concentrations were 163, 240, 160 and 144Bq/m^3 with medians of 160, 168, 124 and 133Bq/m^3, respectively. *N Celik* performed the same study in 2008 in the city of Giresun in Turkey and showed that the volume activity varied from 52 to 360Bq/m^3 [20]. Carlos Sainz et al showed in 2009 that the radon volume activity was 2659Bq/m^3 in Romania and 366Bq/m^3 in the region of Spain [21]. Tetsuya Sanada et al. estimated the radon volume activity in the city of Japan in 2021 [22]. *Takoukam Soh Serge Didier* evaluated the volumetric activity in dwellings in the city of Douala in Cameroon in 2019 [2]. The authors also showed that construction materials contribute to the increase in radon exposure. MF Máduar 2016 showed that buildings constructed with phosphogypsum slabs from ore mining tailings strongly increase the radon volume activity in these buildings [23]. Abd-Elmoniem A. Elzain in 2014 showed the exhalation rate of radon in building materials in Sudan [24].

The soil

Soil is the source of cross-sectional exposure of radon. *Deborah Tolulope Esan* assessed the level of radon from soil on the lithological units of a university in Southwestern Nigeria in 2020 [25]. *Darren Huxtable* 2016, measured radon in gases coming from the ground in cities in Ukraine. In Spain in 2015, V. Moreno et col showed the dynamics of radon in the fault zones of Amer [26]. This study highlighted the influence of seasons on radon measurement. *G Cinelli* made the assessment of radon gas in the soil of the city of Bolsena in Italy in 2014 and developed on the basis of the measurement results a radiometric map of this city [27]. Several mining sites were also of interest to the authors. These are Manganese [28], Uranium [29], Phosphate [30] and Gold [31] sites.

The outside air

Several studies have shown that radon is also present in the outdoor air despite the natural ventilation system. Areas with high background gross radiation (hills [32,33], mining sites [29], granite quarries [31], etc.) present a high dose rate with the high contribution of radon and its progeny [34]. *M Kümmel* in 2014, are interested in the assessment of outdoor radon in mining areas [34,35]. This compartment of radon exposure was also of interest in studies conducted in Brazil in 2002 [36] and in Norway in 2011 [37,38].

Radon Measurement Techniques

After analysis of the articles, it was noticed that the techniques of radon measurement are multiple and depend on the nature of the medium of measurement. Thus, each technique leads to obtaining a dosimetric quantity on the source term (radon). The present literature review has shown three types of measurement techniques, namely: the spectrometric technique, the liquid scintillation technique and the passive method technique based on Solid Nuclear Trace Detectors (SNTD).

Liquid scintillator

The liquid scintillator principle is often used for the measurement of radon concentration in water. The water samples are taken in cleaned and sealed glass bottles of usually 60ml capacity [39]. For the measurement, the samples are placed under a probe connected to an electrode of the measuring device, SMART RnDuo (Portable Radon Monitor), in which a liquid scintillator is installed. The system is connected to an electronic circuit responsible for analyzing the signals and displaying the results according to the incorporated database.

Passive measurement

The principle of continuous (passive) radon measurement is generally used for monitoring radon exposure in homes (bedrooms, schools, offices, mosques, etc.). The principle of detection and measurement is based on the accumulation of gamma radiation interactions emitted during the decay of radon or its progeny with the detection medium. In the literature, solid state nuclear trace detectors are the most widely used for monitoring radon levels in premises. Specifically, the Columbia Resin-39 solid nuclear trace detector (SNTD) is the most widely used in the scientific literature (Figure 3). The DSTN was developed by the National Institute of Radiological Sciences (Chiba, Japan) as a 222Rn and 220Rn discriminating monitor [22]. The monitor is composed of two electrically conductive hemispheres and there are two polycarbonate films installed in the center of the two hemispheres. To isolate and separate the progeny species of 222Rn and 220Rn, a glass fiber filter is located in the first hemisphere. So only 222Rn and 220Rn gases can pass through the filter and enter the first hemisphere. This monitor has two different diffusion chambers that have relatively large and small ventilation rates. This system was developed based on the large difference in half-lives of 222Rn and 220Rn. The detectors are positioned at a distance of 1m from the floor and 0.5m from the side walls of the rooms, through a wire, in the lowest inhabited rooms. The accumulation period is generally three (03) months. After exposure, the films are first subjected to chemical etching with a mixed solution of 8mol/L KOH and 20% C_2H_5OH at 30 ∘C for 30 min. Then, the films are electrochemically etched at 800V and 2000Hz for 2h. The radon concentration is determined by the density obtained on the film. This facilitates its use in studies of radon level monitoring in premises.

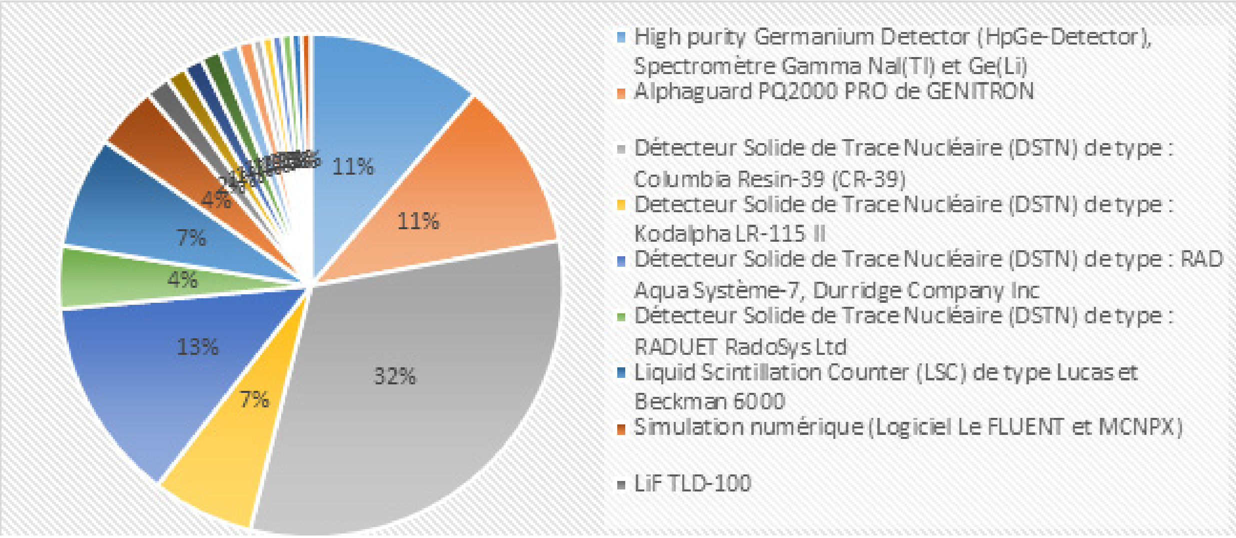

Figure 3: Distribution of detectors used in the literature for the measurement of radon-222 and 220.

Spectrometry

There are two types of spectrometry: gamma and alpha. Gamma and alpha spectrometry is based on the principle of interaction of gamma and alpha radiation emitted during the decay of radon and its progeny with the detection medium, which is generally liquid nitrogen. The system includes an electronic part for signal processing (number of counts/second) and display of the measured dose. This radon measurement system can be fixed in a laboratory. Thus, the measurement is carried out on a sample taken in the medium of measurement (ground and water). Nowadays, there are portable spectrometers that can be used to measure radon in the different compartments described above. Their use is limited in studies in passive measurements (monitoring of radon level in premises) because of the high purchase cost of the number needed for this type of study. Radon measurement therefore responds to several techniques depending on the exposure compartment studied. Thus, through this review, we have evaluated the rating of each measurement technique according to the exposure source. The table below presents the results of this analysis.

Evaluation of 222RN and 220RN measurement techniques in the different natural exposure compartments

Table 2: Evaluation of radon measurement techniques according to the source of radon exposure.

Techniques	Critères d'évaluation								Grandeur Dosimétrique	Score total sur 7
	Faisabilité de la technique	Mobilité du détecteur	Autonomie électrique du détecteur	Coût et utilisation à grande échelle	Disponibilité du détecteur	Nature du milieu de mesures	Type de métrologie			
							Passive	Active		
Détecteurs Solide de Traces Nucléaires	0	1	1	1	1		0	0	Bq/L	4
Scintillateur Liquide	1	0	0	0	1		0	1	Bq/L	3
Spectrométrie (gamma & alpha)	1	1	0	0	1		0	1	Bq/L	4
Détecteurs Solide de Traces Nucléaires	1	1	1	1	1	Habitations	1	0	Bq/m^3	6
Scintillateur Liquide	0	0	0	0	1		0	0	Bq/L	1
Spectrométrie (gamma & alpha)	1	1	0	0	1		0	1	Bq/s	4
Détecteurs Solide de Traces Nucléaires	0	1	1	1	1	Sol	0	0	Bq/m3	4
Scintillateur Liquide	0	0	0	0	1		0	0	Bq/L	1
Spectrométrie (gamma & alpha)	1	1	0	0	1		0	1	Bq/s	4
Détecteurs Solide de Traces Nucléaires	1	1	1	0	1	Air extérieur	1	0	Bq/m3	5
Scintillateur Liquide	0	0	0	0	1		0	0	Bq/L	1
Spectrométrie (gamma & alpha)	1	1	0	0	1		0	1	Bq/m3	4

To carry out this evaluation, we have identified seven (07) criteria. These are: the feasibility of the technique, the mobility of the detector, the electrical autonomy of the detector, the cost and the large-scale use of the detector, the availability of the detector, the nature of the measurement environment and the type of metrology (active or passive). Each criterion has a score of 1. A positive response to an evaluation question is worth a score of 1. A negative response is worth a score of 0. Table 2 presents the results of this evaluation. The analysis of this table shows that detectors based on the liquid scintillation principle (RAD 7 H_2O and SMART RnDuO) are only used for radon measurements in water. The detectors based on the spectrometric principle (HpGe and AlphaGUARD PQ 2000Pro) are also used but as a second choice due to the sampling method. From the same table, it appears that Solid Nuclear Trace Detectors

(SNTDs), mainly of the CR-39 type, are used for continuous measurement with delayed readings (passive dosimetry) of indoor radon activity in premises (bedrooms, schools, churches, mosques, offices, etc.). They can be used for outdoor radon measurement but a constraint of protection against the weather. Techniques based on spectrometry or plastic scintillator are very little used for active indoor radon measurement. This is justified by the fact that these are the places where the aim of the exposure monitoring is oriented towards the health impact of radon on the human being who stays there. Also several factors related to the interaction radiation matter influence this measurement and it is necessary to take them into account in order to obtain a representative measurement of the real exposure situation.

Factors Influencing Radon Measurement

Radon being a gas, its measurement in the different exposure compartments is influenced by several factors: natural ventilation and factors influencing radon transport (humidity, porosity, diffusion coefficient, emanation factor). I Cozmuta ER van der Graaf and RJ de Meijer, in the Netherlands, demonstrated in 2003 that for humidity levels above 80%, the radon release rate decreases very strongly while for lower humidity levels, the radon release rate increases linearly [39]. Nguyen Dinh Chau 2005, in Poland showed that sample mass, particle size and water content influence the rate of radon mass exhalation [40]. Cameron E. Lawrence et al in Australia showed in 2008 that 226Ra activity concentration, soil grain size and soil porosity have a marked effect on 222Rn flux densities. This study proved that surfaces with vegetation have a higher radon exhalation flux density compared to barren surfaces [41]. Specifically, N. Sulekha Rao et al. in India showed in 2009 that the concentration of radon and thoron in dwellings varies with the season. High values of radon and thoron volume activity were found in winter while they are low in summer and rainy season [42]. K Kozak calculated in 2011 in Poland the seasonal correction factors for each month of the year for the concentration of radon volume activity in dwellings [43].

Distribution of Detectors Used in the Literature

Starting from the quantities measured at the types of detectors, we analyze with the help of the circular diagram below the proportions of each type of detectors in the whole of the research and on the whole of the studied regions. The observation and analysis of this diagram leads us to two main points. First, we have a multitude of types of radon detectors that are used in the scientific world (21 in total). Secondly, the DSTN detectors type CR-39 and RAD Aqua system-7 are the most used and appeared in the literature at the world level with respective proportions of 32% and 13% of the present literature review. We have noticed that the techniques are mostly based on continuous measurement using passive detectors.

Directory of the Most Used Detectors in the Literature

In the option to carry out our study and be more objective, we have chosen the radon detectors with at least a percentage of 4% of appearances in the world literature to continue our study (Figure 4). These are eight passive detectors of radon-222 and 220. The graph below presents the evolution of these detectors with a rate of representativeness greater than or equal to 4% in the literature by research region from 2000 to 2021. In the set of radon detectors, we notice from 2005 to 2015 a period of strict growth of appearances from 6 to the peak 29 (in 2015). Over the 22 years of research. We obtained a range of 27 occurrences (with 2 as minimum and 29 as maximum) and an average of 13 counts per year. We observe a similarity of pace between the curve of evolution of the DSTN of type CR-39 (with 101 appearances that is 32%) and that of the whole. Apart from CR-39, the Alphaguard PQ2000 Pro from Genitron (37 appearances, i.e., 12%) and HpGe Detector (with 40 appearances, i.e., 13%) have a constant appearance over the period and the research regions. On the other hand, on the graph we can notice an irregularity and a rarity on the numerical simulation method (which varies over the period between 0 and 2).

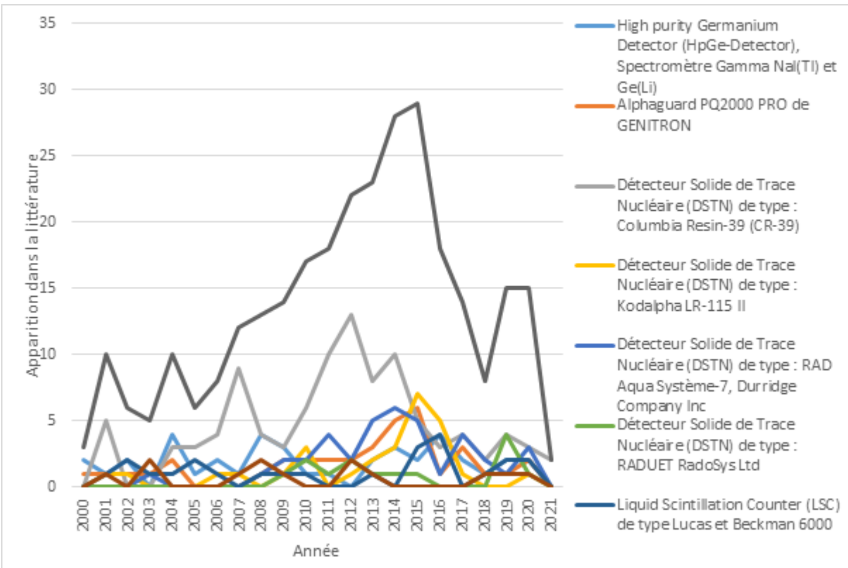

Figure 4: Distribution of the most representative detectors (≥4%) in the literature.

Sub-Regional Analysis of Radon Detectors Used on the African Continent

Aspiring to identify the adequate measurement equipment for the measurement of radon-222 and thoron-220 in Benin, we have reframed the 8 detectors at the level of the African literature (Figure 5). This is illustrated in the graph below. When we observe this graph, we notice the presence of seven (07) out of eight (08) radon detectors. A strong presence, in general, of solid nuclear trace detectors (i.e., 85%) and more particularly the type CR-39 representing almost half of the radon detectors used in the African literature (i.e.,9/20 of the radon detectors). Numerical simulation (FLUENT and MCNPX software) does not appear on the African continent. Cameroon and Nigeria are the two most representative African countries with three different radon detectors and in number respectively 10 and 4 radon detectors. Egypt follows with three radon detectors that is two DSTN type CR-39 and 01 DSTN type Kodalpha LR-115 of type II.

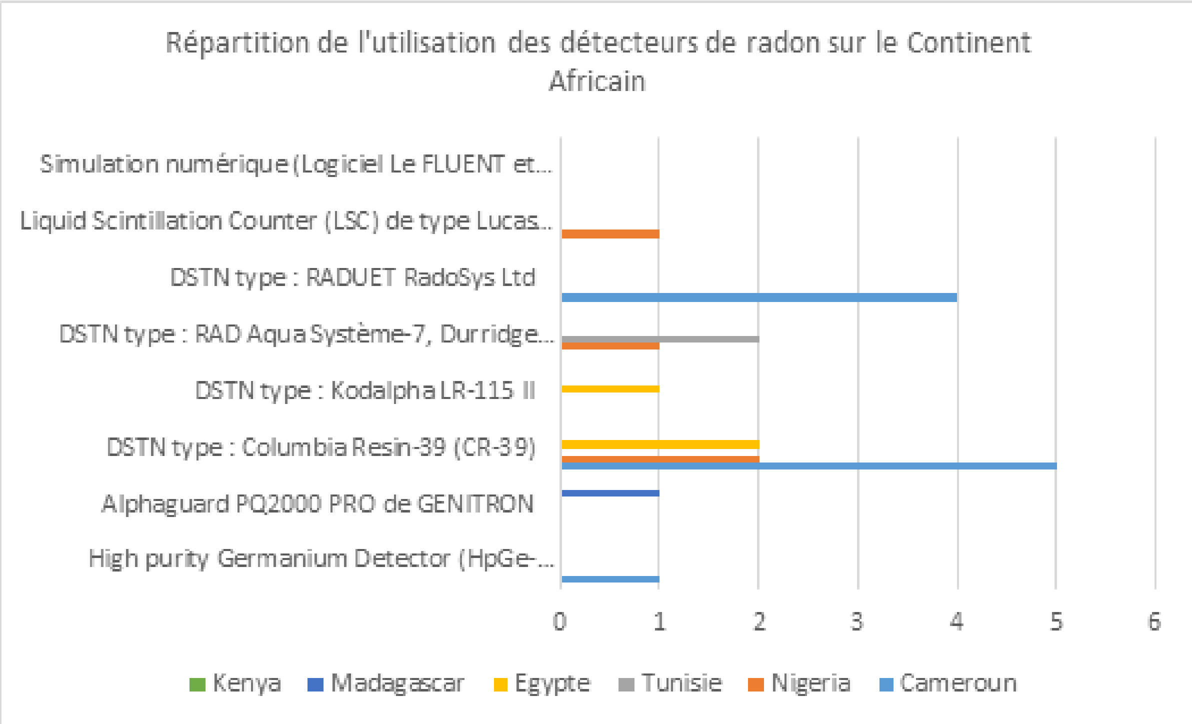

Figure 5: Distribution of the use of the eight (8) radon detectors on the African continent.

Discussion

The present study provided an inventory of detectors and methods used in the literature for monitoring exposure due to radon-222 and thoron-220. It focuses on the measurement techniques for radon-222 and the dissociation of its contribution to external and internal exposure from radon-220. The literature review shows that the methods and materials depend on the objective of the measurement. Radon measurement methods have undergone much evolution. Several uncertainties have been eliminated in order to have more precision in the measurements. Allodji and colleagues, in 2012, identified six uncertainties in measurement systems that were decreased from about 47% in the period 1956-1974 to 10% after 1982 [29]. Solid nuclear trace detectors have seen increasing use after 2010. This is justified by the ICRP recommendations in its publication 103 and the requirements made to IAEA member states for monitoring exposure due to rdon-222 and thoron-220 [8-10]. For proof, the scientific world of Africa in this case Cameroon, Nigeria and Egypt have been concerned through more than five to nine publications each. In 2015, SAÏDOU and collaborators used the solid nuclear trace detector type CR-39 to perform the discriminative measurement of Rn-222 and 220 [44]. In July 2019, SAÏDOU et al showed that the mass activity of 238U was 13-52Bq/Kg and the volume concentration of radon in dwellings in the Poli area of Cameroon [45] using the gamma spectrometry (HpGe) technique and CR-39 type DSTN detectors, respectively. Yet previously in May 2014, the same authors were interested in the volume concentration of radon-222 in the Poli and Lolodorf areas of Cameroon using the E-PERM Electret Ion Chambers (EICs) system [46]. It is possible that this technique presented uncertainties in the measurements made. This would have justified a return to the CR-39 DSTN detector technique. Furthermore, in August 2019, TAKOUKAM et al showed that the concentration of radon-222 is between 31±1 and 436±12Bq/m^3 in the city of Douala in Cameroon using the CR-39 type RADUET detector [2]. These different results and several other series of scientific studies carried out on radon-222 and its peers [44-46] have allowed the Cameroonian authorities to set up a scientific team with a renowned laboratory as well as a national radon-222 monitoring program in the cities selected as potentially having high natural radioactivity. In the context of radon exposure assessment, the measurement technique is a very crucial point. Based on the results in (Table 2), Solid State Nuclear Trace Detectors (SSNTD) are the most widely used in the world literature. Diana Linzmaier and Annette Röttger used HPGe spectrometry system (NaI) to develop a reference of 150 Bq/m^3 to 2000Bq/m^3 based on the precisely known emanation of Rn-222 from a Ra-226 activity standard [47]. This configuration has reduced uncertainties and increased the traceability range of commercial radon meters. The same is true of the research by Allodji and colleagues who identified six uncertainties in radon measurement in 2012 [29]. This study showed that the total size of the uncertainty decreased from about 47% in the period 1956-1974 to 10% after 1982, illustrating the improvement of the radiological monitoring system over time. As for the measurement techniques, they are specific to each measurement context and to the nature of the metrology. This justifies the need to evaluate the techniques before proceeding with the implementation of a protocol on radon measurement.

Conclusion

This systematic review of the literature made it possible to understand that no scientific study has yet been conducted on radon-222 exposure in Benin. It allowed us to understand that different African countries and all over the world have studied the problem of natural exposure due to radon. We have identified three specific techniques of radon measurement. These techniques depend on the objective of the measurement and the nature of the measurement site. The implementation of these techniques requires the use of specific detectors such as DSTN (CR-39, RAD 7, LR-115, RADUET), LSC, *Hp*Ge and Alphaguard. For the measurement of radon concentration in homes, the CR-39 type DSTN is the most used even in the African context. For the quantification of radionuclides present in the soil including radon and its progeny, the active measurement technique based on the High purity Germanium Detector (HpGe-Detector) is the most widely used. For the measurement of radon concentration in water, detectors based on the liquid scintillation technique such as RAD Aqua System-7, Durridge Company Inc. and Liquid Scintillation Counter (LSC) type Lucas and Beckman 6000 are the most used. This review allows us to look at the technique based on the CR-39 solid state nuclear trace detector, the High purity Germanium Detector (HpGe-Detector) and the Liquid Scintillation Counter (LSC) to assess the exposure of radon 222 and 220 respectively in homes, soil and drinking water in the mountainous areas of Benin, in this case the towns of Glazoué and Dassa-Zounmè.

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