Radon and thoron radiation exposure of the Angolan population living in adobe houses

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Received: 26 March 2020 / Published online: 25 May 2020
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Abstract

This study investigates radon and thoron activity concentrations in adobe houses of Angola. Activity concentrations were recorded by passive detectors in rainy and dry seasons in 40 dwellings located at three areas with different climatic and geological backgrounds (Cabinda, Huambo, Menongue). Regarding seasonal and spatial variations, radon activity concentrations are higher in the rainy than in the dry season and both radon and thoron levels are the highest in Huambo, the central part of the country. The number of adobe houses above certain radon and thoron levels were estimated and the contribution of thoron to the inhalation dose was significant.

Keywords Adobe building material · Radon · Thoron · Inhalation dose · Hypothesis testing

Introduction

For a couple of decades, radon has been a subject of research due to its potential risk causing lung cancer. It is considered the second most important cause of lung cancer after smoking [1]. Radon-222 is a radioactive gas in the naturally occurring decay chain of ^{238}U . Radon is hazardous because of its mobility and due to its 3.8 day half-life what consequently leads to accumulation in closed places [2]. In another hand, radon-220, called otherwise thoron, another isotope of radon from the ^{232}Th decay chain, has been usually ignored given its short half-life of 55.6 s [3].

Thoron contribution to the inhalation dose has been already proven [4–7] what further triggered surveys focusing on this isotope [8–12]. Many studies have proven high levels of thoron in houses made of unburnt earthen material (like soil or clay), or adobe, a block made of soil and water dried in ambient conditions in sunlight. In Germany, a study

conducted in houses made of clay, the thoron annual inhalation dose was found to be as high as 4 mSv a^{-1} [3]. In China, a research made in traditional houses proved a thoron contribution up to 56.6% to the inhalation dose [13]. In Hungary, the same contribution went up to 30% in adobe houses [14].

In Africa, research works mostly have been focusing on radon but not thoron. In some countries like Ghana, Nigeria, Kenya and Cameroon [8, 11, 15, 16], an effort is being made to collect reference data based on which national radon action levels can be derived. Nevertheless, a few studies on both isotopes are reported. In Kenya (at the coast region), in houses made of soil, 25% of the surveyed houses showed values above 1000 Bq m^{-3} of thoron activity concentration and the mean was 652 Bq m^{-3} [8]. In Cameroon, a study at a high natural radiation area of Bikoué and Ngombas located in the uranium region of Lolodorf reported a contribution of thoron to the inhalation dose by up to 78.5% [17].

Despite the fact that adobe houses are popular in Africa mostly in the sub-Saharan part, research on their natural radiation is scarce. A survey in a modern suburb of Ghana where most houses were built from the 90's to date shows that 28% of houses are still made of adobe [18]. In Angola, no recorded studies were made on radon and thoron, and especially not in adobe houses where the inhalation doses received by residents are potentially elevated. The main aim of the present study is to evaluate the radon and thoron radiation risk in the adobe house of Angola.

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Studied areas

Three geologically and climatically different areas, Cabinda, Huambo and Menongue have been chosen for this study from the North, central and South parts of Angola, respectively (Fig. 1). Basic information of their geology, NORM (Naturally Occurring Radioactive Materials) content in local adobe [19], especially that of the parents of radon and thoron, and their climate are provided bellow separately for the three areas. Information about geological

features described in this section was taken from “*Notícia Explicativa da Carta Geologica de Angola*”, a summary of the geology of Angola made by the National Institute of Geology in 1977, reviewed and updated in 1992 [20]. In general about the climate, Angola is a tropical country and only two main seasons are identified, the rainy (November–May) and the dry (June–October) seasons. Weather data detailed are taken for the monitoring period between November 2014 and October 2015 from the “*OpenWeather*” website history [21], which uses data from local weather stations. The NORM content of adobe

Fig. 1 Sampling sites in 1—Cabinda, 2—Huambo and 3—Menongue on the sketch of the geological map of Angola taken from *Geologia de Angola* by De Araujo (1992) [20]. Geological features on the map are as follows, a) Pleistocene to Cretaceous marine sediments,

b) Archean to Proterozoic metamorphic and igneous rocks, c) Belts of the upper Proterozoic (Pan-African of age), d) Sedimentary from Tertiary to Quaternary, e) Mesozoic to Paleozoic sediments

building material was previously investigated [19] and below a relevant summary of these data is provided.

Cabinda

The geology of Cabinda province is characterized by various formations aging from Precambrian to Holocene, including Pleistocene marine deposits at the coastal area. The climate is humid tropical. The radon and thoron activity concentration measurements were done at the coastal part of the main city, where the humidity is very high in both seasons around 85% (Fig. 2a). Higher temperatures are registered during the rainy season with an average of 27 °C than in the dry season with an average of 23 °C (Fig. 2b). During the monitored year, total precipitation was 244 mm for the rainy and 2 mm for the dry season (Fig. 2c). Previous results of the NORM content of adobe in this area showed values ranging between 15–45 and 27–49 Bq kg⁻¹ for radium (²²⁶Ra) and thorium (²³²Th), respectively (Fig. 3; [19]).

Huambo

The geology of Huambo province consists of old (Archean to Proterozoic) metamorphic (gneiss, micaschist, metasediments) and igneous (granite, rhyolite to andesites) rocks. At Huambo city, Palaeocene–Eocene laterites were also mapped. The climate is highly influenced by the altitude, i.e. 1700 m above the sea. In the rainy season, the average humidity is 84% and in the dry season, it is 51% (Fig. 2a). The average temperature during the rainy season is 19 °C and during the dry season is 20 °C (Fig. 2b). Precipitation registered during the monitoring period was 522 mm for the rainy and 79 mm for the dry season (Fig. 2c). This area showed the highest NORM contents in adobe building materials with the following ranges: 49–116 and 39–121 Bq kg⁻¹ for ²²⁶Ra and ²³²Th, respectively (Fig. 3; [19]).

Fig. 2 Box and whisker plots of **a** humidity, **b** temperature values and **c** bar chart of total precipitation in rainy (R) and dry (D) seasons [21] at the studied areas during the survey period

Fig. 3 Box and whisker plots of **a** ²²⁶Ra and **b** ²³²Th contents of adobe building material samples from the same studied areas [19]

Menongue

The geology of Menongue study area is based on Archean gneiss, Proterozoic rhyolite-andesite and Tertiary–Quaternary Kalahari sediment formations. Menongue has a semi-desert climate influenced by the desert of Namibe. The humidity is much higher during the rainy (78%) than during the dry season (33%, Fig. 2a). The temperature difference between daytime and night is around 10 °C during the rainy season and 20 °C during the dry season. The average temperature in the rainy season is 21 °C and in the dry season is 22 °C (Fig. 2b). Precipitation data registered during the monitored period gives a total of 573 mm and 24 mm for the rainy and the dry seasons, respectively (Fig. 2c). Results of NORM in adobes (Fig. 3; [19]) showed 15–56 and 17–57 Bq kg^{−1} for ²²⁶Ra and ²³²Th, respectively.

Methods

Sampling strategy

A pair of passive radon and thoron detectors were used separately for the rainy and dry seasons in a one year monitoring period in 2014–2015. The rainy season was recorded by a measurement campaign from the beginning of November 2014 to the end of April 2015, whereas the dry season campaign took from the beginning of May to the end of October 2015. The exposure time was 180 ± 5 days. Fifteen houses per area, in total 45 houses were monitored. Only those results were analysed where values were available about both radon and thoron in both rainy and dry seasons, making a total of 40 dwellings. For the placement of the detectors, two aspects were considered. The first one is the possibility of disturbance of the measurement by the residents or visitors of the surveyed dwellings, and the second one is the efficiency of measuring thoron. The distance of the detector from the wall, therefore, was around 9 ± 1 cm and the height around 2 m (when not placed behind a cupboard). All detectors were placed in living rooms as the only place made available by the owners.

Etched track passive detectors

In this study, to monitor radon and thoron activity concentrations, RADUET type etched track passive detectors were used which are commercially available at several locations of Radosys Ltd. (headquarter at Budapest, Hungary). This is a detector composed of two electroconductive cylindrical plastic chambers containing CR-39 plastic nuclear track detector (PNTD). The mentioned chambers are made in a way that one is restricted to detect thoron and the other can detect both radionuclides. Radon and thoron activity

concentrations are determined after the PNTDs are etched and alpha tracks are identified and counted with a proper reading system [22]. These detectors are a result of collaborative work between NIRS, Japan and Radosys Ltd., Hungary. Calibration, detector analysis, reading results and radon and thoron activity concentration calculations together with uncertainty estimation were all performed by the manufacturer, Radosys Ltd.

Evaluation methods

Inhalation dose estimation

To evaluate the health risk of the population living in the monitored houses, inhalation dose from radon and thoron were estimated based on Eq. 1 [23].

$$D_i = 10^{-6} * C_{av} * F_{eq} * F_c * O \quad (1)$$

where D_i is the estimated annual inhalation dose from radon or thoron (mSv y^{−1}), C_{av} is the annual average radon or thoron activity concentration (Bq m^{−3}), F_{eq} is the equilibrium factor which is 0.4 for radon [24] and 0.04 for thoron [25], F_c is the dose conversion factor, which is 9 nSv/(Bq h m^{−3}) for radon and 40 nSv/(Bq h m^{−3}) for thoron [24] and finally, O is the annual indoor occupancy time (7012.8 h y^{−1}). Note that without direct determination of thoron decay product activity concentrations and equilibrium factors, the thoron doses estimated with the applied average discrete value (0.04) are loaded with high uncertainty.

Statistical analyses

Various statistical methods have been used to allow variable analyses, data comparison and interpretation by the “Origin” and “Statgraphics” software. Basic statistics have been calculated and represented in box and whisker plots. Simple regression was plotted to check the relationship between different variables. Statistical distributions were analysed by the cumulative frequency histogram and tested for normality and lognormality by the Shapiro–Wilk hypothesis test. Lognormality was tested using the natural logarithm of the data. If the P value is less than 0.05, we can reject the idea that the sample comes from the suggested distribution with 95% confidence. For comparison of medians of sample groups and for checking if the differences are statistically significant, the Mann–Whitney hypothesis test was performed. The null hypothesis is that the median of a chosen group of samples is equal to the median of the other one. The alternative hypothesis is that the medians are different. For P values less than 0.05, the alternative hypothesis is accepted, whereas for P value greater or equal to 0.05, it is rejected at the 95% confidence level.

Results

Basic statistics of seasonal indoor radon and thoron activity concentrations

Basic statistics of radon and thoron activity concentrations are summarized in Table 1 and the box and whisker plots of Fig. 4a and b. Averages with corresponding standard deviations and medians in brackets [average $\pm$ standard deviation(median)] of radon during rainy and dry seasons respectively are $38 \pm 11(36)$ and $22 \pm 8(20)$ Bq m⁻³ in Cabinda, $130 \pm 39(118)$ and $94 \pm 31(83)$ Bq m⁻³ in Huambo, and $65 \pm 19(62)$ and $53 \pm 15(52)$ Bq m⁻³ in Menongue. For thoron, the same results are as follows,

$155 \pm 92(164)$ and $169 \pm 97(159)$ Bq m⁻³ in Cabinda, $262 \pm 137(236)$ and $293 \pm 136(240)$ Bq m⁻³ in Huambo, and $83 \pm 54(60)$ and $101 \pm 59(76)$ Bq m⁻³ in Menongue, respectively, for rainy and dry seasons. To check if the medians of the activity concentrations are different between the seasons and if the differences are statistically significant, the Mann–Whitney test was performed. Results of the *P* values for radon and thoron, respectively, are as follows, 0.0003 and 0.73 in Cabinda, 0.046 and 0.74 in Huambo and 0.067 and 0.92 in Menongue. Accordingly, for radon, differences are statistically significant between the two seasons, except in Menongue. For thoron activity concentrations, the differences between rainy and dry seasons are statistically not significant in all areas.

Table 1 Basic statistics of radon and thoron (Bq m⁻³) for both seasons (rainy and dry) in the three different areas

Location	Season	Count	Min	L. quartile	Median	U. quartile	Max	Range	Mean	St. dev.	St. skewness	St. kurtosis
Cabinda	Radon	Rainy	14	26	26	36	40	68	42	38	11	2.90
		Dry	14	12	12	20	29	39	27	22	8	0.71
	Thoron	Rainy	14	28	28	164	235	297	269	155	92	0.01
		Dry	14	22	22	159	244	323	301	169	97	0.06
Huambo	Radon	Rainy	12	75	108	118	171	180	105	130	39	0.07
		Dry	12	42	77	83	120	152	110	94	31	0.36
	Thoron	Rainy	12	113	156	236	302	518	405	262	137	1.09
		Dry	12	122	229	240	327	560	438	293	136	1.13
Menongue	Radon	Rainy	14	41	52	62	72	113	72	65	19	1.35
		Dry	14	31	43	52	64	77	46	53	15	0.22
	Thoron	Rainy	14	20	49	60	128	194	174	83	54	0.91
		Dry	14	47	69	76	103	237	190	101	59	1.87

Fig. 4 Box and whisker plots of measured **a** radon and **b** thoron activity concentrations (Bq m⁻³) in both rainy and dry seasons in Cabinda, Huambo and Menongue

Annual average indoor radon and thoron activity concentrations

Results of the annual average indoor radon and thoron activity concentrations are summarized in box and whisker plots (Fig. 5a, b). Radon and thoron averages, respective standard deviations and medians in brackets are $30 \pm 8(29)$ and $163 \pm 93(161)$ Bq m⁻³ in Cabinda, $112 \pm 31(103)$ and $278 \pm 134(242)$ Bq m⁻³ in Huambo, and $55 \pm 13(53)$ and $98 \pm 57(76)$ Bq m⁻³ in Menongue, respectively. In the box and whisker plots, Huambo shows the highest annual average radon and thoron activity concentrations. The lowest median is measured in Cabinda for radon and in Menongue for thoron. The Mann–Whitney hypothesis test was performed comparing the medians of the activity concentrations among all areas. *P* values of the different comparisons for radon and thoron are, respectively, 0.0000087 and 0.021 for Huambo versus Cabinda, 0.000033 and 0.000064 for Huambo versus Menongue, and 0.000013 and 0.025 for Menongue versus Cabinda. These results show significant differences among medians of all studied areas for both annual radon and thoron activity concentrations.

Estimated inhalation doses

Estimated annual inhalation doses of radon and thoron at the three areas are 0.75 ± 0.19 and 1.82 ± 1.04 mSv y⁻¹ in Cabinda, 2.83 ± 0.8 and 3.12 ± 1.5 mSv y⁻¹ in Huambo, and 1.49 ± 0.4 and 1.03 ± 0.6 mSv y⁻¹ in Menongue, respectively (Fig. 6a). The total inhalation doses per area are 2.0 ± 0.8 , 4.5 ± 1.5 and 2.0 ± 0.6 mSv y⁻¹ in Cabinda, Huambo and Menongue, respectively (Fig. 6b).

Statistical distributions

The sample distribution was ascertained by the frequency histogram and Shapiro–Wilk test (Fig. 7a, b). For both radon and thoron, normal distribution was rejected by the Shapiro–Wilk test that shows a *P* value equal to 0.00055 for radon and 0.000091 for thoron. On the other hand, the test does not reject the hypothesis of radon and thoron coming from a lognormally distributed population with *P* values equal to 0.14 for radon and 0.09 for thoron. Both tests are performed with 95% confidence.

Discussion

Seasonal variation of radon and thoron activity concentrations

With the aim of evaluating the effect of climatic conditions on indoor radon and thoron activity concentrations in Angolan adobe houses, the one year survey period was divided into two seasons (rainy and dry). As seen in Fig. 4a and proven by Mann–Whitney tests (*P* value equals 0.0003 in Cabinda, 0.046 in Huambo), medians of the indoor radon during the rainy season show statistically significantly higher values than in the dry season in Cabinda and Huambo. The elevated indoor radon activity concentrations during rainy seasons can be explained by the influence of precipitation. Adobe building material, showing soil properties, has the ability to absorb water [14]. It is also important to emphasize that most indoor radon comes from the ground under the dwellings. The moist content of pore spaces both in the adobe and the soil may increase the emanation coefficient and consequently the exhalation of radon [26, 27], thus the level of radon activity concentration in the rainy season.

Fig. 5 Box and whisker plots of annual average **a** radon and **b** thoron activity concentrations (Bq m⁻³) in Cabinda, Huambo and Menongue

Fig. 6 Box and whisker plots of **a** estimated doses from radon and thoron, separately, (mSv y⁻¹) and **b** total inhalation doses (mSv y⁻¹) from Cabinda, Huambo and Menongue

Fig. 7 Frequency histogram showing the distribution of radon and thoron concentrations

Another factor might be the behaviour of the residents who tend to seal their homes when the weather is worse. Results of the present study are consistent with one carried out in Ghana [28] and in Cameroon [12] where radon levels were also elevated during the rainy season (medians of rainy and dry seasons were respectively found to be 39.3 and 26.9 Bq m⁻³ in Ghana and 131 and 80 Bq m⁻³ in Cameroon). Both studies explained the difference by the common practice of inhabitants of closing windows during rainy season. Regarding Menongue, the difference is statistically not significant (*P* value equals 0.067, Fig. 4a). The possible explanation of this variance is that having a semi-desert climate, diurnal temperatures of Menongue are very high (above 35 °C) causing rapid evaporation of the water accumulated in the soil. Consequently, only a small amount of water can accumulate in the pore space influencing radon exhalation. The inhabitants are also less probable to close their windows. Although temperature could play a principle role in seasonal variations of the indoor radon levels, the differences in the average temperatures among seasons are generally very small in Angola as it was the case during the monitored period (4 °C in Cabinda and 1 °C in Huambo and Menongue, Fig. 2b). A comparison of the medians of the annual averages of the indoor thoron, on the other hand, does not show significant differences between the seasons (*P* value equals 0.73 in Cabinda, 0.74 in Huambo and 0.92 in Menongue; Fig. 4b).

Spatial variation of radon and thoron activity concentrations

Box and whisker plots in Fig. 5a and b show the annual average indoor radon and thoron activity concentrations at the three studied areas. As seen in results the Mann–Whitney (*P* values of the different comparisons for radon and thoron are, respectively, 0.000009 and 0.021 for Huambo versus Cabinda, 0.000033 and 0.000064 for Huambo versus Menongue, and 0.000013 and 0.025 for Menongue versus Cabinda) test ascertains that activity concentrations in Huambo, the central part of the country are the highest among the three areas. These results can be explained by the differences in geology. In fact, in this area, the geology is composed of metamorphic (gneiss, micaschist, metasediments) and igneous (granite, rhyolite to andesites) rocks which can contain the higher abundance of mother nuclides of radon and thoron in the area. In the previous study of the authors [19] the highest values of ²²⁶Ra and ²³²Th in adobe building materials from the same dwellings (116 and 121 Bq kg⁻¹ respectively; Fig. 3), confirm the above stated. Radon and ²²⁶Ra [19] show a correlation coefficient of 0.46 with a *P* value of 0.0042 (Fig. 8a). This proves that there is a relationship between radon and its source. However, it worth taking into consideration that the correlation would be better if we had radon coming specifically from the building material. As known, most indoor radon comes from the underlying dwelling foundation and some studied dwellings are without coverage on the floor. In these cases, radon coming from the floor may considerably contribute to the indoor levels. This result is consistent with those of Saidou et al. [17] who studied adobe dwellings from Cameroon.

Fig. 8 Correlation between **a** radon and ²²⁶Ra and **b** thoron and ²³²Th. The activity concentrations of ²²⁶Ra and ²³²Th were measured in adobe building material samples taken from the dwellings

where the indoor radon and thoron measurements took place. These data and more details of the methodology were published in a previous study of the authors [19]

Contrary to the case of radon, there is not a statistically significant relationship between thoron and its source, ^{232}Th [19], which show a correlation coefficient of 0.29 and a P value of 0.08 (Fig. 8b). This is even more surprising considering that at 9 ± 1 cm distance from the adobe walls and at a 2 m height, where the detectors were placed, the only source of thoron is the building material itself (in case of radon the contribution of the soil cannot be excluded). The explanation can be that thoron measurements are more disturbed by other factors like ventilation and humidity than radon, because of its shorter half-life [14, 29]. The equilibrium factor of thoron is generally influenced by indoor atmospheric parameters such as ventilation more strongly than that of radon [3]. Because thoron diffuses very slowly, any ventilation can prevent its accumulation near the walls which disturbs the measurements. Thus, it is hard to have the full amount of thoron coming from the building. For this reason, the correlation between thoron and the source can be even less significant than between radon and its source.

Number of dwellings with activity concentrations above recommended values

Both radon and thoron activity concentrations show lognormal distributions (Fig. 7). Therefore, a lognormal probability plot for both isotopes can be drawn with the 95% confidence intervals (Fig. 9). The plot for annual radon average therefore indicates that there is a 95% probability, that 10 to 32% of adobe houses in Angola, assuming the representativity of our sampling, are above the recommended limit for indoor

radon concentration of 100 Bq m^{-3} (Fig. 9a; [30]). However, none of the houses exceed the stronger recommendation of 300 Bq m^{-3} annual average radon activity concentration.

For thoron, the lognormal probability plot (Fig. 9b) shows that there is a 95% confidence, that 59 to 81% of adobe houses in Angola are over 100 Bq m^{-3} and 6 to 28% are over 300 Bq m^{-3} . Despite the fact that many studies are reporting high levels of indoor thoron [4–7, 17, 31] (Table 2), as well as its high potential contribution to the inhalation dose, no limit concentration was yet recommended for thoron. Therefore, the 100 and 300 Bq m^{-3} values serve as reference values and not as any kind of limit or recommended values. For the appropriate understanding of these data, one must also note that the thoron activity concentrations were measured at a fixed distance, 9 ± 1 cm away from adobe walls and that it is expected to show high inhomogeneity indoors.

Inhalation radiation risk in Angolan adobe houses

According to the results in the present study (Fig. 6), the annual radon inhalation dose is particularly significantly higher in Huambo ($2.83 \pm 0.8 \text{ mSv y}^{-1}$) than the world-wide average (1.15 mSv y^{-1} [32]). The other two studied areas are below the reference value. Moreover, when thoron is included in the estimation, total inhalation dose is about two times higher (Fig. 6). As already mentioned by Tokonami et al. 2001 [4], thoron may have an important contribution to the inhalation dose. In the present study, the average thoron contribution is calculated to be 50%, which shows the potentially high significance of this

Fig. 9 Lognormal probability plots of annual average **a** radon and **b** thoron activity concentrations with estimates of the number of dwellings above certain levels

Table 2 Comparison of radon and thoron activity concentrations in different countries

Country	Building material	Location	Radon activity concentrations (Bq.m ⁻³)			Thoron activity concentrations (Bq.m ⁻³)			Reference
			Average	Geometric mean	Range	Average	Geometric mean	Range	
Angola	Adobe	Cabinda	30±8	29	21–45	162±93	130	26–310	Present study
		Huambo	112±31	108	71–166	278±134	252	118–539	
		Menongue	59±16	57	40–95	92±55	81	44–213	
		All samples	65±39	55	21–166	172±121	134	26–539	
Hungary	Adobe	Great Hungarian Plain	194	166	45–609	245	211	33–576	Szabó et al. 2014 [14]
Cameroon	Adobe	Poli and Lolorio	92±3	72	27–937	260±13	213	48–700	Saidou et al., 2015 [17]
China	Earthen building material ^b	Many different locations	72±59	58±2	x ^a —427	318±368	162±4	x ^a —1860	Shang et al. 2005 [13]
China	Earthen building material ^b	Shanxi and Shaanxi	91	57	19–195	351	153	10–865	Tokonami et al. 2004 [34]
Canada	Building material non identified	Ottawa	110	74±2	8–1525	56	19±4	5–924	Chen et al., 2008 [35]
Cameroon	Building material non identified	Douala	139±47	118±1	31–436	80±52	62±2	4–246	Takoukam et al., 2019 [11]
Japan	wooden houses with soil walls	Hiroshima	26±11	—	—	85±16	—	—	Doi and Kobayashi 1994 [5]
Korea	mud walls	six different cities	22	—	—	82	—	—	Chung 1998 [6]
Japan	Building material non identified	Gumma	22±14	—	11–93	22±18	—	3–97	Tokonami et al. 2005 [22]
Hungary	Building material non identified	Kövágószölös	154	—	17–1083	98	—	1–741	Kavasi et al., 2006 [33]
Germany	Clay houses	Bavaria	20 - 160	—	—	—	—	10–90	Gierl et al., 2014 [3]
Macedonia	Building material non identified	regional survey	—	—	—	37±36	28±2	3–272	Stojanovska et al., 2013 [36]
Mexico	Building material non identified	regional survey	—	—	—	82	55	8–234	Martinez et al., 2004 [37]
Kenya	Earthen building material ^b	Mirma Hill	35	—	16–56	652	—	132–1295	Chege et al. 2015 [31]

^aData not available.^bEarthen building materials are those made of soil, clay or similar

isotope in inhalation dose estimations, even when considering the high uncertainty of the present calculation. Other studies also showed significant thoron contribution to the inhalation dose. In traditional (made of soil) Chinese houses, thoron contributed up to 57% to the total dose [13]. Hungarian adobe houses showed an average thoron contribution of 30% [14]. A study on radon and thoron

in houses made of soil bricks carried out in Cameroon showed a thoron contribution of up to 79% [17]. From the referred results, it is clear that radon is not enough to access the total annual inhalation dose in adobe or similar houses, and that the total radon and thoron radiation risk in Angolan adobe houses is not negligible and worth further considerations.

Comparison with other countries

The results of the present study are compared to those made in other countries (Table 2). The type of building material is similar to adobe but in some cases (Ottawa-Canada, Douala-Cameron, Gumma-Japan, Kővágószőlős-Hungary, (North-) Macedonia, Mexico, Table 2) the investigation was a general survey in dwellings or workplaces, where the type of building material was not taken into account. An effort was made to choose studies, where passive detectors were used for a better comparison.

Comparing indoor radon activity concentration averages, results of Huambo ($112 \pm 31 \text{ Bq m}^{-3}$) are among the four greatest values showing only Kővágószőlős (Hungary; former uranium mining area; 154 Bq m^{-3} [33]), the Great Hungarian Plain (Hungary; 194 Bq m^{-3} [14]) and Douala (Cameroon; $139 \pm 47 \text{ Bq m}^{-3}$ [11]) higher values (Table 2). Results from Cabinda and Menongue are among the lowest values (30 ± 8 and $59 \pm 16 \text{ Bq m}^{-3}$, respectively) but still higher than those of Gumma (Japan; $22 \pm 14 \text{ Bq m}^{-3}$ [22]), Hiroshima ($26 \pm 11 \text{ Bq m}^{-3}$ [5]) and Korea (22 Bq m^{-3} [6]).

Indoor thoron activity concentration averages give different classifications. Studies made in adobe or similar building materials have much higher activity concentrations than Cabinda ($162 \pm 93 \text{ Bq m}^{-3}$) and Menongue ($92 \pm 55 \text{ Bq m}^{-3}$). However, values from Huambo ($278 \pm 13 \text{ Bq m}^{-3}$) are still among the highest after Mirma Hill (Kenya; 652 Bq m^{-3} [31]) and Shanxi and Shaanxi (China; 351 Bq m^{-3} [34]).

Conclusion

Seasonal and spatial variations of the radon and thoron activity concentrations in Angolan adobe houses at three, geologically and geographically different study areas were detected in this study. Radon activity concentrations are higher during the rainy season than in the dry season, whereas no statistically significant differences were detected for thoron. Annual average radon and thoron activity concentrations at around 9 cm from adobe walls are the highest in Huambo (central part of the country). Seasonal variations are essentially most probably due to precipitation variability, and spatial variations are mostly due to differences in geology and the mother nuclide content of adobe. Radon and thoron activity concentrations are sampled from a lognormally distributed population based on hypothesis testing. Regarding radon activity concentrations, 10 to 32% of adobe houses in Angola are above the recommended limit of 100 Bq m^{-3} and when it comes to thoron activity concentrations, 59 to 81% of adobe houses in Angola are expected to be over 100 Bq m^{-3} , and 6 to 28% of them are probably over 300 Bq m^{-3} (as reference values). The inhalation dose in Huambo ($4.5 \pm 1.5 \text{ mSv y}^{-1}$) is estimated to be above the worldwide average (1.15 mSv

y^{-1}). The contribution of thoron to the inhalation dose is shown to be 50% which refers to its significance even when considering the uncertainties of the calculation. The total inhalation dose received by residents in Angolan adobe houses is not expected to be negligible and it worth further investigations. The results of this study are valuable information on radon and thoron in Africa in general and in Angola in particular.

Acknowledgements Open access funding provided by Eötvös University (ELTE). This project is financed by the Higher Education Department of the Angolan Army (FAA). J. Salupeto-Dembo is thankful for the support of all the members of the Lithosphere Fluid Research Lab of the University Eötvös University (particularly: Nelson, Silvana, Laszlo, Abel, Thomas, Csilla). The work of Zs. Szabó-Krausz is funded by the Premium Postdoctorate Research Program of the Hungarian Academy of Sciences. A big thanks to Mr. Erik Hulber and the workers of the Radosys Ltd., Hungary. Our thanks are extended to people in Angola who made possible the field campaign: Regue, Agostinho, Adelaide, Lelo, Mestre, Bruno, Bemba, Nangueve, Tio Bino, Sr Sapundo, Sr David, Fifi, and all the local people for their trust. We cannot forget the special help from Mr. António Dembo and Mrs. Lizeth Pena. We are also thankful for the work of the editor and for the review. This is the 101st publication of the Lithosphere Fluid Research Laboratory (LRG), Eötvös University.

Compliance with ethical standards

Conflict of interest We state that all measurements were done with the appropriate information and permissions of house owners and we declare that we have no conflicts of interest to disclose.

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