Exposure to radon in buildings in the municipality of Lubango, Angola, during winter months

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Abstract

The evaluation of indoor radon exposure in dwellings is done for the first time in Lubango. The corresponding annual effective dose to which the population is exposed during the wintertime was calculated. A total of 59 single-family houses and 16 public buildings were selected. The results obtained show that in 100% of the houses, the radon concentrations are below 300 Bq m^{-3}. The values of the indoor annual effective dose vary from (2.0 ± 0.1) to (7.0 ± 0.2) mSv y^{-1} below the recommended maximum reference level of 10 mSv y^{-1}.

Keywords Radon concentration · World Health Organization · Annual effective dose · Lubango

Introduction

The population's exposure to radon occurs mainly through inhalation, resulting in irradiation of lung and, to a lesser extent, other organs. However, under conditions of very high concentrations in drinking water, ingestion may be the main source of exposure to organs other than the lung. The measurement of radon and its descendants has become extremely relevant since it was recognized as the main contributor to the dose of natural radiation to which the population is subject. Radon has been classified by the World Health Organization (WHO) as a carcinogen [1], the second leading cause of lung cancer, after tobacco smoke, contributing between 3 and 14% of the cases. The lower the radon concentration, the lower the risk associated with that exposure, although there is no known low threshold for the associated cancer risk [2–6]. The WHO established a recommended annual

average concentration of 100 Bq m^{-3}. However, if this level cannot be achieved under each country's specific conditions, the reference level should not exceed 300 Bq m^{-3} [1].

The radon travels inside buildings through the rocky substrate, water wells, fractured rocks, drainage infrastructure, pits, foundations, linings, cracks, and windows due to the establishment gradients of atmospheric pressure, humidity and temperature, which influence radon exhalation. The radon concentration in the air can be measured using passive detectors, (SSNTDs, Solid State Nuclear Track Detectors) like the CR-39, which is particularly well suited for measurement in homes. This detector records the presence of alpha particles for a period that, in most cases, is no less than 30 days.

The number of radon studies carried out so far in Angola is scarce. Recently three studies addressing the exposure to gamma radiation [7], radon and thoron gas [8] and presence of radon in water [9] have been published. Our study has the aim to carry out a population dosimetric study in order to determine the average concentrations of housing radon and calculate the effective annual dose to which adults and children are exposed in the city of Lubango, located on the Huíla plateau, Angola. In geological terms the region presents granitic formations and a large amount of magmatic rocks, but the amount of these rocks as well as the level of natural radioactivity are variable. A significant amount of work must be made to assess the radiological environment under which the Angolan population are subject to. The lack of legislation on radon exposure might be part of the explanation for

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this apparent lack of interest on the subject. Risk assessment is important as a guide to action. Studies [10] show that about half of the average annual dose of natural radiation can come from radon in buildings. It is necessary to reduce the risks of those exposed to radon concentrations above the limit level recommended by WHO, both in homes and workplaces. Simple mitigation procedures, such as the use of fans, sealing floor and wall cracks, can reduce the radon concentration in the air to acceptable levels [11].

The city of Lubango has a mineralization with large scintillometer values, twenty times higher than the background radiation. As far as it is known, studies in this area in Angola are a novelty, and the aim is to develop a population dosimetric study to determine the average concentrations of residential radon, calculate the effective annual dose to which the populations are subjected and, if necessary, recommend mitigation mechanisms. All measurements were made during the winter months. A new campaign is foreseen for the summer months.

Location of study and geological setting

This study focuses on the extreme southeast of Angola in Lubango, the capital city of Huíla province, located in the Huíla plateau. It has approximately 876,000 inhabitants, an area of 3147 km^2 and an average altitude of 1790 m.

Angola is in the inter-tropical region (the equator, to the north, and the Capricorn Tropic to the south). Its climate is dependent on predominant climatic factors such as latitude, atmospheric circulation and the incidence of solar rays, but also on typical and intrinsic factors of the region such as the cold Benguela current, in the Atlantic Ocean and the topography of the region. Angola's climate is by nature seasonal, characterized by hot and humid summers (October to May) and cold and dry winters (June to September) [12]. Lubango has an average annual temperature of 18 °C and is probably the city with the mildest and more temperate climate in Angola [13]. Figure 1 is a graphic presentation of available annual temperature records [13]. The location of Lubango on the Angola map is presented in Fig. 2.

In geological terms, Lubango is characterized by granitic ornamental rocks [14]. Filled pegmatite and aplite, are frequent, especially in the areas occupied by the migmatite rocks. Among all these rocks of precambrian age, there is an intimate connection, given its genesis-anatexis. From the primitive substrate, represented by gneisses, amphibolite and mica-shale, there are vestiges in several points of the area. Igneous rocks of different natures and several units, such as gabbro with or without olivine, norites, orbiting, dolerites with or without olivine, porphyries, lamprophyre (thickets), andesites, basalt-olivine, etc., outcrop in certain profusion in the area. Rocks of sedimentary origin, more or less
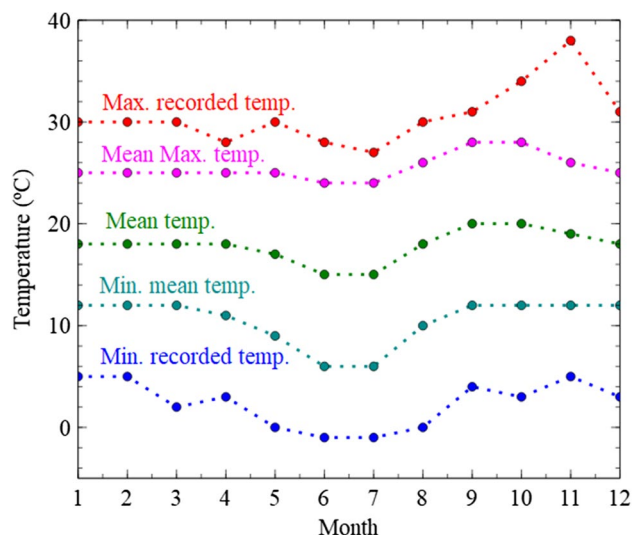

Fig. 1 Graphical presentation of annual temperature records of Lubango as of September of 2020 (adapted from [13]). Lines are only to guide the eye

metamorphosed (sandstone and quartzites), also appear in the area, lying directly on the granite. In terms of Economic Geology, there are occurrences of minerals such as Native Molybdenum, and Native Copper, Mica (Muscovite) and Gold (this element exists, although in a small percentage, in the alluviums of the Mungondo River, a little downstream of the place where it is located the occurrence of mica mentioned above) [15–18].

Methods

Sampling strategy

In the early 1990s, Angola experienced moments of civil war, leading people to abandon unstable regions and concentrate on more peaceful regions, the city of Lubango in particular. This is one of the reasons that led to the city's urban diversification. Thus about 37% (N = 28) of the buildings selected are predominantly adobe, while 63% (N = 47) are brick buildings. Of the assessed buildings 76% (N = 57) are of the ground floor type, 11% (N = 8) are single-story, 12% (N = 9) are two-story and three-story buildings respectively. The largest assessed building was the Lubango Central Hospital, with 8 floors, contributing 1% (N = 1).

To measure the radon concentration, a passive technique was used with CR-39 detectors. These solid-state nuclear track plastic chips of 10 × 10 mm^2, are integrating and lightweight detectors, placed inside a cylindrical diffusion chamber sensitive to radon, that are commonly used for long-term radon measurements [22–26]. They have been fixed with strong adhesive tape in order to avoid changes of position.

Fig. 2 Map of Angola and
Lubango Municipality, done
using ArcMap 10.3 [19, 20]
and its shapefiles (adapted from
MapCruzin.com [21])
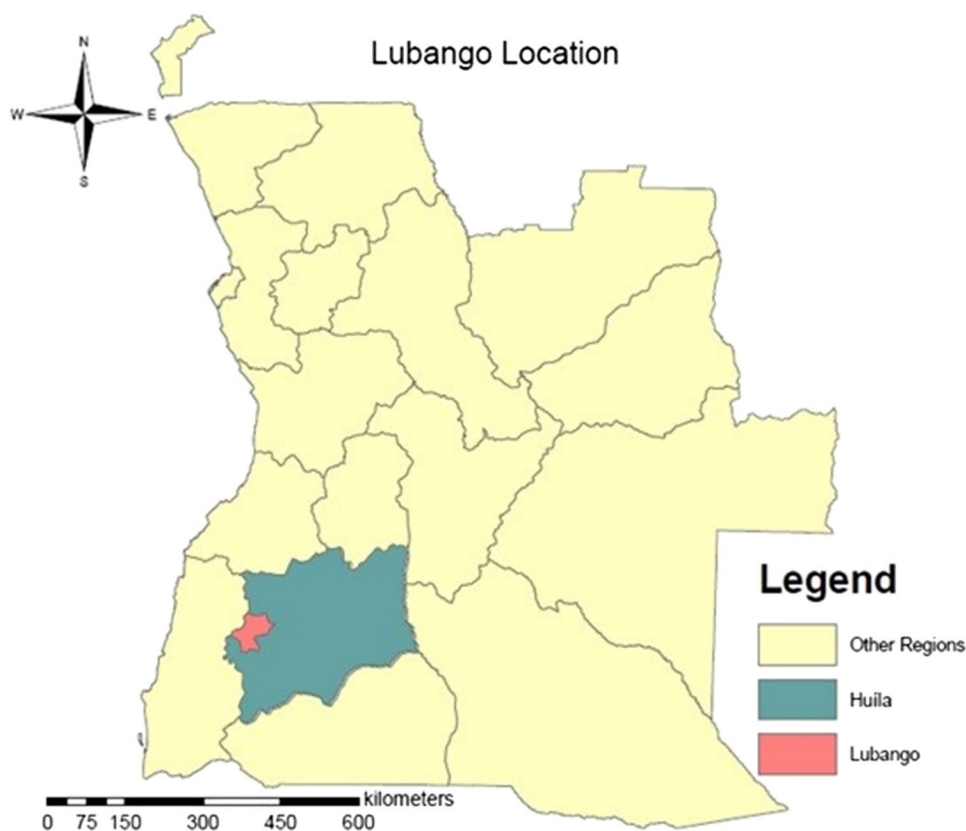
To minimize possible errors associated with environmental variations during the placement of the detectors, they were placed the same day in the morning by a team trained for this purpose. To evaluate the potential of radon exposure, 164 detectors were used, 75 housing units were selected and divided in two distinctive groups of dwellings: a first group was composed by 16 Public Buildings in which 96 SSNTD CR-39 were deployed on the ground floors at 1 m above the ground [27, 28] for a period of 90 days [29, 30], during the winter, where workers and students stay most of the time, such as public institution offices, teacher's rooms, classrooms, laboratories, diagnostic and medical treatment offices, etc. A second group was composed of 59 single-family homes in which 68 detectors were also deployed with the same conditions, where the residents stay most of the time, such as in the dining room or the bedrooms for 90 days, also during the winter. The collection of all detectors was carried out by the same team responsible for their placement and following the same order and plan of intervention. The detectors were placed away from the walls, preferably affixed to furniture, cupboards, etc. On the other hand, detectors have been placed in larger quantities in public institutions, because there is a higher population density, more individuals are exposed to radon. No detectors were placed in the house basement because the residents did not stay there for a long time. The main objective of placing all detectors 1 m

from the ground and all of them on the ground floor, is to place all detectors in the same conditions, and because the radon is denser than the atmospheric air, it accumulates in the lower areas of the buildings, and at precisely the same height that we remain for the longest time sitting, or even sleeping.

In this work measurements were conducted only during the cold season. As indicated in Fig. 1, temperatures can fall below 10º C. During this time people have the tendency to keep windows and doors of homes closed, facilitating the build-up of radon inside. As a matter of habit, in this season of the year the population of Lubango returns home just after sunset, around 6 p.m., staying home on average 11 h a day. These facts favor the choice of wintertime for conducting the present study since higher indoor concentrations are expected over what could be obtained in summertime.

Radon activity concentration detection

After the 90 days period, the detectors were sealed and transported by plane to LabExpoRad laboratory at Covilhã, Portugal. After etching chemically all detectors in a 6.25 M, NaOH solution at 90 º C for 220 min, the detectors were washed with distilled water and dried for a few minutes. The number of alpha tracks in each detector was automatically counted using a Radosys Microscope (Fig. 3).

Fig. 3 Radosys Microscope at Covilhã's laboratory

The Radon Activity Concentration C_{Rn} (RAC) is given by the following equation [31]:

$$C_{Rn} = \frac{(T_D - T_{D0})CF}{t} \quad (\text{Bq} \cdot \text{m}^{-3}) \tag{1}$$

and

$$T_D = \frac{n_g}{S} \quad (\text{track} \cdot \text{mm}^{-2}) \tag{2}$$

where t is the exposure time (in hour), CF the calibration factor of the specific batch of detectors (in Bq h $(\text{m}^3$ track $\text{mm}^{-2})^{-1}$), automatically provided by the Radosys QC system, T_D the number of tracks n_g after exposure per scanned area S and T_{D0} is the background track density. The factory default for T_{D0} is 0.3 track mm^{-2} [31], but it is recommended to obtain T_{D0} experimentally. In this case n blank detectors are developed and processed in the same way as the exposed ones and the average number of background tracks $\overline{n_b}$ in the scanned area obtained. The value of T_{D0} is then computed as

$$T_{D0} = \frac{\overline{n_b}}{S} \tag{3}$$

The uncertainty of radon concentration measurement, according to norm ISO 11665-4: 2012(E9) [32], is computed as:

$$\sigma_{C_{Rn}}^2 = \omega^2 \left(n_g + \frac{\overline{n_b}}{n} \right) + C_{Rn}^2 \left(\frac{\sigma_\omega}{\omega} \right)^2 \tag{4}$$

where ω is given by:

$$\omega = \frac{CF}{t.S} \tag{5}$$

and

$$\left(\frac{\sigma_\omega}{\omega} \right)^2 = \left(\frac{\sigma_t}{t} \right)^2 + \left(\frac{\sigma_S}{S} \right)^2 + \left(\frac{\sigma_{CF}}{CF} \right)^2 \tag{6}$$

Radon map preparation

A color map of the radon concentration distribution was drawn using Geographic Information System [33–35]. Deterministic interpolation techniques were used, which create surfaces from measured points, based on the Inverse distance Weighted [36]. This interpolation assumes that each measured point has a local influence that diminishes with distance. Thus, points in the near neighborhood are given high weights, whereas points at a far distance are given small weights [37].

Annual effective dose assessment

In order to compute the annual effective dose D_{eff} we apply the following equation proposed in the UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) publication [38] was used:

$$D_{eff} = C_{Rn}FTD_{CF} \quad (\text{mSv} \cdot \text{y}^{-1}) \tag{7}$$

where D_{eff} is the annual effective dose per year, C_{Rn} is the arithmetic mean radon concentration in Bq m^{-3}, F is taken to be 0.4 the recommended equilibrium factor value, T is the indoor occupancy time of 7000 h per year [2], D_{CF} is the dose conversion factor for radon and its recommended value is 9×10^{-6} mSv $(\text{Bq h m}^{-3})^{-1}$ [1]. Only values in the wintertime were obtained in this study. From the literature [39], it is expected that these values are higher than the ones for summertime. The obtained annual effective dose in this work, will thus be overestimated.

Table 1 Mean radon concentration for Public Buildings. A total number of 96 detectors were deployed

Code	Locality	Number of detectors	Building materials	Mean RAC (Bq m^{-3})
1	Ademar Damião	4	Brick	81 ± 3
2	Administração Municipal do Lubango	4	Brick	130 ± 4
3	Instituto Médio de Economia do Lubango	4	Brick	99 ± 3
4	Instituto Superior Politécnico da Huíla	2	Brick	83 ± 3
5	Escola Portuguesa do Lubango	4	Brick	119 ± 4
6	Escola Secundária do Lubango	4	Brick	93 ± 3
7	Hospital Central do Lubango	4	Brick	128 ± 4
8	Escola 14 de Abril	4	Brick	110 ± 4
9	Escola 27 de Março	4	Brick	134 ± 4
10	Administração Comunal do Hoque	10	Brick	157 ± 3
11	Administração Comunal da Huila	16	Brick	158 ± 3
12	Administração da Arimba	3	Brick	262 ± 9
13	Maternidade	10	Brick	168 ± 3
14	Escola Secundária da Arimba	6	Brick	111 ± 3
15	Mapel	6	Brick	71 ± 2
16	Instituto Superior de Ciências da Educação da Huíla	11	Brick	223 ± 5

Table 2 Mean of radon concentration for Single-Family Home. A total number of 68 detectors were deployed

Code	Locality	Number of detectors	Buildings Materials	Mean RAC (Bq m^{-3})
17	14 de Abril	3	Adobe or Brick	79 ± 3
18	Arco íris	1	Brick	109 ± 7
19	Arimba	1	Adobe	83 ± 5
20	Bairro da Lage	3	Adobe or Brick	103 ± 4
21	Benfica	5	Adobe or Brick	109 ± 3
22	CDTE Cowboy	6	Adobe or Brick	160 ± 5
23	CDTE Nzagi	5	Adobe or Brick	89 ± 3
24	Dr António Agostinho Neto	1	Brick	99 ± 6
25	Ferrovia	2	Adobe or Brick	88 ± 4
26	Helder Neto	4	Brick	213 ± 6
27	João de Almeida	3	Adobe or Brick	111 ± 4
28	Lalula	3	Brick	165 ± 6
29	Laureanos	1	Brick	76 ± 5
30	Lucrécia	3	Adobe or Brick	88 ± 5
31	Mapunda	5	Brick	197 ± 5
32	Minhota	2	Brick	94 ± 4
33	Mitcha	5	Adobe	108 ± 3
34	Mutundo	1	Adobe	167 ± 10
35	Nambambi	4	Adobe	111 ± 3
36	Senhora do Monte	5	Brick	133 ± 4
37	Sofrio	1	Adobe	198 ± 11
38	Tchioco	4	Adobe	87 ± 3

Results and discussion

Radon concentration

The mean radon concentration and annual effective dose are presented in Tables 1 and 2.

Analyzing the data on Tables 1 and 2 we conclude that the highest and the lowest mean radon concentration values in public building, are respectively (262 ± 9) Bq m^{-3} at Administração Comunal da Arimba and (71 ± 2) Bq m^{-3} at Mapel. For single-family homes, the highest and lowest values are respectively (213 ± 6) Bq m^{-3} in Helder Neto quarter and (76 ± 5) Bq m^{-3} in Laureanos quarter.

Overall, the radon concentration values measured in Lubango cover a wide range, between 20 and 497 Bq m^{-3}, with a mean of 136 Bq m^{-3}. The lowest occurrences of radon concentration occur in the city center. On the other hand, higher values of radon concentration were measured in the north western and southern regions since those areas are near the mountains and crossed by some rivers where granitic rocks abound.

The radon concentration values, depending on the type of building material, brick and adobe, do not differ significantly in terms of results due to the fact that the bricks are manufactured with the resources existing in the soils of the Lubango region, such as silica, alumina (clay), etc.

Similar studies were made in some other regions of Angola during the winter, namely Cabinda, Huambo and Menongue, although with smaller number of deployed detectors when compared with the present study. Radon activity concentration of 22 Bq m^{-3}, 94 Bq m^{-3} and 53 Bq m^{-3} were respectively found [8]. These values are
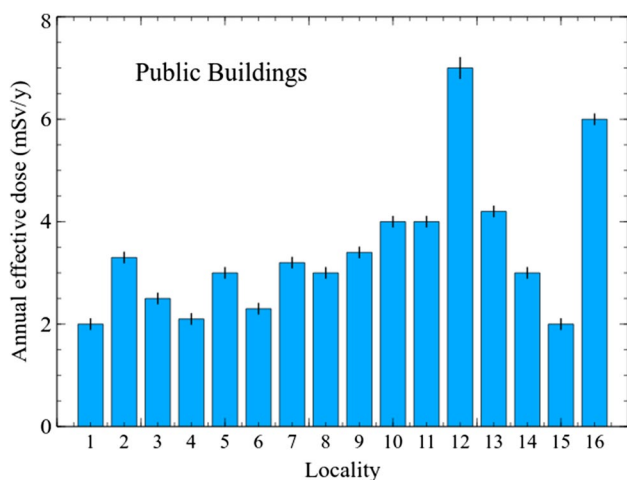

Fig. 4 Annual effective dose in Public Buildings. The locality code is the same as in Table 1
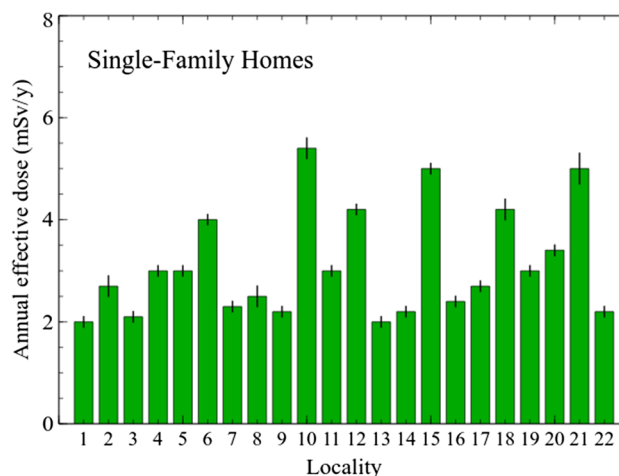

Fig. 5 Annual effective dose for Single-Family Homes. The locality code is the same as in Table 2

lower than those found in the city of Lubango, where larger granite areas can be found.
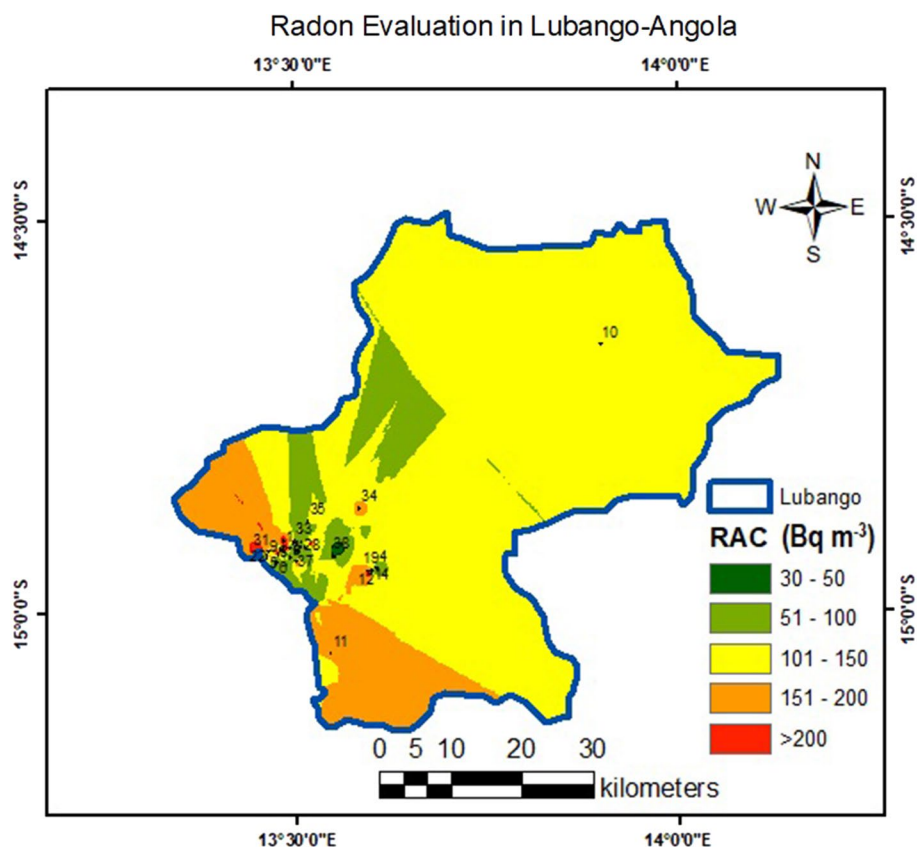
Annual effective dose

Using Eq. 7 values of annual effective dose have been computed for public buildings (Fig. 4) and single-family homes (Fig. 5). The annual effective dose in public buildings and in single-family homes varied from (2.0 ± 0.1) mSv y^{-1} to (7.0 ± 0.2) mSv y^{-1}, higher than some places in Namibia [40], the neighboring country. The global average of 3.4 mSv y^{-1} is higher than the average dose from inhaling radon from all sources, which is approximately 1 mSv y^{-1} [10] and is also higher than the total natural exposure to radiation of 2.4 mSv y^{-1} [41]. The annual effective dose is in the recommended action interval level between 3 and 10 mSv y^{-1} [42].

For comparison purposes, elsewhere in the country, estimated annual inhalation doses of radon are 0.75 ± 0.19 mSv y^{-1} in Cabinda, 2.83 ± 0.8 mSv y^{-1} in Huambo, and 1.49 ± 0.4 mSv y^{-1} in Menongue, respectively [8], lower than those recorded in the city of Lubango.

Map of radon concentration in Lubango Municipality

For graphic and georeferencing purposes, 164 points scattered around the city of Lubango were used to build a radon map according to the method explained in Sect. 3.3. According to this map (Fig. 6) there is a heterogeneous spatial radon distribution in Lubango Municipality, with relatively higher values in the northwest region, while the lowest values were observed in the southeast region. The number of detectors is still relatively small for a definitive conclusion to be made.

Fig. 6 Map of radon concentration in Lubango Municipality, made using ArcMap10.3 [19, 20] and its base map adapted from ESRI [43]

Conclusion

The measured average concentration of radon gas in the city of Lubango was 136 Bq m^{-3}, corresponding to an added average annual effective dose to the population of 3.4 mSv y^{-1}. The highest values were recorded at Administração Comunal da Arimba (public buildings) and at Helder Neto (single-family homes). Although these results are within the range recommended by ICRP, it will be necessary to increase the population's awareness of the radon problem in residences and in the public buildings, improving ventilation, depressurization and filtration. In the future more data points in Lubango municipality will be acquired to have a more comprehensive overview of the situation.

These results will also serve as a starting point for population dosimetry studies of regions surrounding the city of Lubango, and later on, the remaining municipalities of Huila province, and other provinces of Angola.

Compliance with ethical standards

Conflict of interest We state that all measurements were done with the appropriate information and permissions of local authorities, in the case of public buildings and house owners in the case of single-family houses. We further declare that we have no conflicts of interest to disclose.

References

1. Zeeb H, Shannoun F (2009) Who Handbook on Indoor radon, a public health perspective. WHO Press, Geneva
2. Louro A et al (2013) Human exposure to indoor radon: a survey in the region of Guarda, Portugal. Radiat Prot Dosimetry 154:237–244
3. Laughlin J, Bochicchio F (2007) In focus: radon and lung cancer. In: Conference: EnVIE conference on indoor air quality and health for EU policy. Helsinki (Finland).199-210
4. Tirmarche M, Harrison JD, Laurier D, Paquet F, Blanchardon E, Marsh JW (2010) Lung cancer risk from radon and progeny and statement on radon. Ann ICRP 40:1–64
5. Axelsson G, Andersson EM, Barregard L (2015) Lung cancer risk from radon exposure in dwellings in Sweden: how many cases can be prevented if radon levels are lowered? Cancer Causes Control 26:541–547. https://doi.org/10.1007/s10552-015-0531-6

6. Tschiersch J, Haninger T (2005) Comments on 'adjusting lung cancer risks for temporal and spatial variations in radon concentrations in dwellings in Gansu Province, China' by Lubin et al. Radiat Res 163:571–579

7. Salupeto-Dembo J, Szabó-Krausz Z, Völgyesi P, Kis Z, Szabó C (2020) External radiation exposure of the Angolan population living in adobe houses. J Radioanal Nucl Chem 323:353–364

8. Salupeto-Dembo J, Szabó-Krausz Z, Völgyesi P, Szabó C (2020) Radon and thoron radiation exposure of the Angolan population living in adobe houses. J Radioanal Nucl Chem 325:271–282

9. Kessongo J, Bahu Y, Inácio M, Peralta L, Soares S (2020) Radon concentration potential in Bibala municipality water: consequences for public consumption. Radiat Phys Chem. https://doi.org/10.1016/j.radphyschem.2020.108951

10. Unscear, Sources and effects of ionizing radiation United Nations Scientific Committee on the Effects of Atomic Radiation. http://large.stanford.edu/courses/2017/ph241/gutwald1/docs/unscear-2-2000.pdf. Accessed 05 April 2020

11. Cottinghan WN, Greenwood DA (2004) An introduction to nuclear physics. Cambridge University Press, Cambridge, United Kingdom

12. Huntley BJ, Russo Vladimir, Lages Fernanda, Ferrand N (2019) Angolan biodiversity: science & conservation: a modern synthesis. Springer Open, Cham, Switzerland

13. Wikipedia.org (2020) Cidade do Lubango. https://pt.wikipedia.org/wiki/Lubango. Acessd 4 March 2020

14. CESO (2020) Estudo Sobre as rochas Ornamentais em Angola. https://www.ceso.pt/pdfs/RochasOrnamentaisAngola.pdf. Accessed 8 March 2020

15. Pereira E, Tassinari CCG, Rodrigues JF, Van-Dúnem MV (2011) New data on the deposition age of the volcano-sedimentary chela group and its eburnean basement: implications to post-Eburnean crustal evolution of the SW of Angola. Comun Geol 98:29–40

16. DA Silva AF (2020) A Geologia da República de Angola desde o Paleoarcaico ao Paleozóico Inferior. Repositório do LNEG/GEOCIÊNCIAS/Geologia e Cartogr. Geológica. http://repositorio.lneg.pt/handle/10400.9/2619. Accessed 10 April 2020

17. McCourt S, Armstrong RA, Jelsma H, Mapeo RBM (2013) New U-Pb SHRIMP ages from the Lubango region, SW Angola: insights into the Palaeoproterozoic evolution of the Angolan Shield, southern Congo Craton, Africa. J Geol Soc London 170:353–363

18. Francisco Sousa do Vale MCS (1971) Carta Geológica: folha nº 336 - Sá da Bandeira1:100.000. http://memoriaafrica.ua.pt/Catalog/ShowRecord.aspx?MFN=12080. Accessed 07 June 2020

19. ESRI (2020) A quick tour of ArcMap. https://desktop.arcgis.com/en/arcmap/10.3/main/get-started/a-quick-tour-of-arcmap.htm. Accessed 03 April 2020

20. ESRI (2020) ArcGIS Desktop,https://desktop.arcgis.com/en/arcmap/. Accessed 06 April 2020

21. Mapcruzin (2020) Download Free Angola Country, city, region, boundaries GIS Shapefile Map Layers. https://mapcruzin.com/free-angola-country-city-place-gis-shapefiles.htm. Accessed 02 April 2020

22. Vasilescu A (2013) CR-39 sampling of indoor radon in Southern Romania. Rom J Phys 58:311–319

23. Koc P, Ekinci N, Cinan E, Kavaz E (2018) Determination of radon concentration by using CR-39 plastic track detectors in dwellings of Bingöl and Mus Provinces of Turkey. Asian J Chem 30:2424–2430

24. Zeng Z, Cheng JG, Li J (2018) Measurements of radon concentrations using CR-39 detectors in China JinPing Underground Laboratory (2015–2016). https://arxiv.org/ftp/arxiv/papers/1806/1806.06567.pdf. Accessed 18 March 2020

25. Lee J (2005) Construction of an environmental radon monitoring system using Cr-39 nuclear track detectors. Nucl. Eng. Technol. 37:395–400

26. Shakir AA, Kadhim IH, Almayyalin AOM, Majeed FA (2016) Measurement of radon concentration in some of cosmetics by using Nuclear Track Detector (CR-39). Int J PharmTech Res 9:231–235

27. Sani JM, Alias N, Ahmad N, Saat A (2018) The assessment of indoor Radon-222 concentration and emanation rate at Gua Penyu, Pahang. Malays J Anal Sci 22:483–490

28. Hasan F (1996) Indoor radon concentration measurements at Hebron University campus: a case study Fakhri L Hasan. J Najah Edu 4:92–107

29. Iida T, Nurishi R, Okamoto K (1997) Passive integrating 222Rn and 220Rn CUP monitors with CR-39 detectors. Environ Int. https://doi.org/10.1016/S0160-4120(96)00166-3

30. Askari M, Hassanvand MS, Naddafi K, Zarei A, Yousefi M, Alimohammadi M (2019) Assessment of indoor radon concentration in residential homes and public places in south of Tehran, Iran. Environ Earth Sci 78:317

31. Radosys (2020) RADOSYS User Manual. https://manualzz.com/doc/7321648/1-introduction-to-the-radosys-system. Accessed 20 January 2020

32. ISO (2020) International Standard 11665-4. https://www.iso.org/standard/76009.html. Acsessed 30 April 2020

33. Kennedy M (2013) Introducing Geographic Information Systems with ArcGIS. Wiley, New Jersey, USA

34. Nas B, Berktay A (2010) Groundwater quality mapping in urban groundwater using GIS. Environ Monit Assess 160:215–227

35. Johnston K, Ver Hoef JM, Krivoruchko K, Lucas N (2001) Using ArcGIS Geostatistical Analyst. GIS by ESRI, New York, USA

36. Shepard D (1968) Two- dimensional interpolation function for irregularly- spaced data. Proc 23rd Nat Conf. https://doi.org/10.1145/800186.810616

37. Shashi Shekhar HX (2008) Encyclopedia of GIS. Spring, New York, USA

38. UNSCEAR (2020) 2000-Sources and effects of ionizing radiation: volume I, https://www.unscear.org/docs/publications/2000/UNSCEAR_2000_Report_Vol.I.pdf. Accessed 11 April 2020

39. Stojanovska Z, Januseski J, Bossew P, Zunic ZS, Tollefsen T, Ristova M (2011) Seasonal indoor radon concentration in FYR of Macedonia. Radiat Meas 46:602–610

40. Munyaradzi Z, Anna KN, Makondelele TV (2018) "Excess lifetime cancer risk due to natural radioactivity in soils: case of Karibib town in Namibia", African Rev. Phys. 13:71–78

41. UNSCEAR (2020) Sources, Effects and Risks of Ionizing Radiation. https://www.unscear.org/docs/publications/1988/UNSCEAR_1988_Report.pdf. Accessed 10 March 2020

42. Brenner DJ (1994) Protection against radon-222 at home and at work. ICRP publication 65. Int J Radiat Biol 66:413

43. ESRI (2020) Basemaps and Imagery, Digital Map Solutions. https://www.esri.com/en-us/arcgis/products/location-services/services/basemaps. Accessed 11 April 2020