BJRS
BRAZILIAN JOURNAL OF RADIATION SCIENCES
doi.org/10.15392/2319-0612.2024.2415
2024, 12(2) | 01-26 | e2415
Submitted: 2023-12-29
Accepted: 2024-04-12

Evaluation of indoor radon gas levels in three Brazilian municipalities located in the state of Minas Gerais

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Abstract: Ionizing radiation, particularly radon exposure, constitutes a significant risk factor for lung cancer, with the World Health Organization identifying radon as the second major contributor to this malignancy. This study investigates radon levels in dwellings across three Brazilian municipalities and explores the interplay between dwelling characteristics, residents' behavior, and radon concentrations equal to or exceeding 200 Bq/m³. Conducted over two seasons, the research measured radon gas concentrations in both the bedroom and living room of each residence. Out of 577 households surveyed, 123 exhibited radon levels meeting or surpassing 200 Bq/m³, with a higher incidence observed in rural areas. Factors associated with elevated radon levels included geographical location in Caldas and Poços de Caldas, residence in rural areas, houses constructed before 1976, and the absence of open windows during the night. The study underscores the prevalence of elevated indoor radon levels, surpassing the World Health Organization's recommended reference level of 100 Bq/m³. Additionally, dwelling characteristics and residents' habits, such as keeping windows closed during sleep, contribute to increased radon concentrations in residential settings.

Keywords: indoor radon, Poços de Caldas Plateau (Brazil), cancer surveillance, lung cancer, ionizing radiation.

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Avaliação dos níveis de gás radônio em ambientes fechados em três municípios brasileiros localizados no estado de Minas Gerais

Resumo: A radiação ionizante, particularmente a exposição ao radonio, constitui um factor de risco significativo para o câncer do pulmão, tendo a Organização Mundial de Saúde o identificado como a segunda principal causa para esta doença. Este estudo investiga os níveis de radônio em residências em três municípios brasileiros e explora a interação entre as características das moradias, o comportamento dos residentes e as concentrações de radônio iguais ou superiores a 200 Bq/m³. Realizada ao longo de duas temporadas, a pesquisa mediu as concentrações de gás radônio tanto no quarto quanto na sala de cada residência. Dos 577 domicilios avaliados, 123 apresentavam níveis de radônio iguais ou superiores a 200 Bq/m³, com maior incidência observada nas zonas rurais. Os fatores associados aos níveis elevados de radônio incluíram localização geográfica em Caldas e Poços de Caldas, residência em áreas rurais, casas construídas antes de 1976 e ausência de janelas abertas durante a noite. O estudo ressalta a prevalência de níveis elevados de radônio em ambientes fechados, superando o nível de referência recomendado pela Organização Mundial da Saúde de 100 Bq/m³. Além disso, as características da habitação e os hábitos dos residentes, como manter as janelas fechadas durante o sono, contribuem para o aumento das concentrações de radônio em ambientes residenciais.

Palavras-chave: radônio indoor, Planalto de Poços de Caldas (Brasil), vigilância do câncer, câncer de pulmão, radiação ionizante.

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1. INTRODUCTION

Cancer constitutes a significant global public health challenge, with its prevalence on the rise worldwide. Approximately 70% of cancer-related deaths occur in low and middle-income countries [1]. In Brazil, recent data estimates by National Cancer Institute (INCA) project 704,000 new cancer cases annually during the 2023-2025 triennium. Lung cancer stands as the second most common malignant neoplasm in men and the fourth most common in women [2].

Ionizing radiation, particularly radon exposure, is recognized as one of the risk factors for lung cancer. The World Health Organization- WHO identifies radon as the second leading cause of lung cancer, following smoking, and as the primary cause among individuals who have never smoked. It is crucial to note that individuals exposed to radon who smoke or are former smokers have a higher likelihood of developing lung cancer (synergistic effect) compared to those who have never smoked [3].

Radon (radon-222) naturally emanates from soil and rocks and tends to accumulate in indoor environments, such as underground mines, homes, or workplaces, due to its gaseous nature. There is no known safe threshold for radon gas exposure, meaning that no level of radon exposure is considered risk-free for public health. Even at low concentrations, exposure to this gas may lead to a slight increase in the risk of lung cancer [3].

Radon is a radioactive gas that occurs naturally as a byproduct of the decay of uranium and thorium in rocks and soils. Soil gas infiltration is recognized as the primary source of residential radon. The half-life of radon gas is 3.8 days, and it is a decay product of radium-226 (with a half-life of 1600 years) and part of the uranium-238 decay chain. Radon concentration varies significantly depending on local geology and factors such as differential pressure between the interior and exterior of a building, ventilation rate, internal heating, meteorological conditions and floor level [4]. Other sources of radon include building materials (such as sandstone, concrete, brick, natural stone, gypsum, or granite) and well or ground water [3].

Once inhaled, radon´s daughters settle in the respiratory tract. Due to its relatively short half-life, decay occurs before its elimination from the lung. Consequently, two radioactive radon decay products, polonium-218 and short-lived polonium-214, emit alpha particles directly into lung tissue. The energy delivered by them during decay is associated with the development of lung cancer [4].

Several studies have concentrated on regions with elevated natural radioactivity worldwide, conducting surveys, radiobiological and epidemiological investigtions. The heightened natural radioactivity in these areas is primarily attributed to geological and geochemical soil structures or the presence of radioactive thermal waters. In municipalities situated on the Poços de Caldas Plateau, there is a concern about a potential association between cancer incidence in the area and exposure to natural radiation. This concern arose due to the discovery of uranium deposits and the establishment of a currently inactive plant for the commercial exploitation of this ore [5]. The Plateau region is widely acknowledged as an Area of High Natural Radiation [6-8].

The correlation between radon exposure and lung cancer is well-established. While epidemiological studies confirm the link between residential radon exposure and an increased risk of lung cancer in the general population, the association with other radon-induced cancers, such as leukemia, has been described but not consistently demonstrated. The potential link between radon exposure and the development of leukemia may be explained by radon's ability to induce genomic instability in normal cells [9].

A study (Cancer Prevention Study-II, Nutrition Cohort) utilizing data from the American Cancer Society, was established in 1992, aimed to examine the association between residential radon exposure at the municipal level and the risk of blood cancer [10]. The findings indicated that women living in areas with the highest average radon concentrations (>148 Bq/m³) had a statistically significant increased risk of hematologic cancer compared to those living in counties with the lowest concentrations (<74 Bq/m³). Similarly, a separate study investigating the impact of environmental radon exposure on childhood leukemia reported a positive but weak association between radon exposure and childhood leukemia in case-control studies [11].

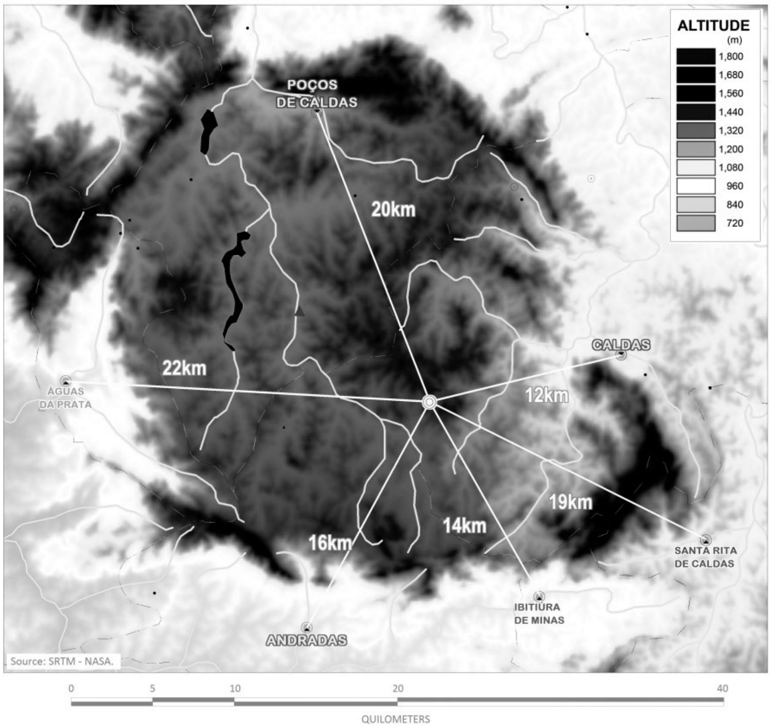
The assessment of radon concentrations in indoor environments is a priority issue given the population's concerns about the incidence of cancer, as previously mentioned [12]. The objective of this article is to investigate radon concentrations inside dwellings in the municipalities of Andradas, Caldas and Poços de Caldas and evaluate the association between household characteristics, residents' behavior and radon concentrations ≥ 200 Bq/m³.

2. MATERIALS AND METHODS

This study was carried out in three municipalities of the Poços de Caldas Plateau - Brazil (Andradas, Caldas and Poços de Caldas), in two distinct occasions, in October of 2012 (spring-summer) and in April and September of 2013 (autumn-winter) with the purpose of measuring the concentration of indoor radon. Alghtough the municipalities of Santa Rita de Caldas and Ibitiura de Minas are part of the group of municipalities representing the Poços de Caldas Plateau, they were deemed ineligible for not meeting the adopted criteria: *i*) distance greater than the 20 km radius from the former uranium mine located in Caldas (Figure 1) and *ii*) in a previous measurement campaign of ambient dose rate [13] no high levels of natural radiation were found. Additionally, the municipality of Águas da Prata was not included because it is in another federal state, outside the region covered by the Minas Gerais State Health Secretariat (SES-MG).

The selected three municipalities cover a territorial area of 1,732 km^2. According to the Brazilian Institute of Geography and Statistics- IBGE [14] there were 202,471 inhabitants, 248 census tracts (the smallest administrative unit) and 60,373 households. The municipality of Andradas with 37,018 inhabitants, 41 census tracts and 10,424 households; the municipality of Caldas with 13,557 inhabitants, 18 census tracts and 3,166 households, and the municipality of Poços de Caldas with 151,896 individuals, 189 census tracts and 46,783 households.

Figure 1: Map of the Poços de Caldas Plateau and municipalities located within a radius of approximately 20 km from the former uranium mine located in the rural area of Caldas.



Source: SRTM-NASA digital model processed by authors.

The study employed households as the primary units of analysis, categorized by urban and rural areas within each municipality as defined by IBGE [14]. The sampling plan employed data from the Aggregate Reference System by Census Tracts of Population Count [14]. The sample was calculated based on territorial coverage in a square grid of 100 meters by 100 meters (residential blocks). Each block received a code (e.g. C144 L197) and its selection was done randomly. It was assumed that each residential block would contribute with one household located at its center or the nearest one possible. In cases where residential blocks were selected without households, the closest neighboring ones were chosen. Dwellings designated for occasional use (temporary use, such as vacation periods, etc.) and not intended for residential purposes were excluded from the study. Although dwellings selection used geographical criteria, the demographical information was used for estimation of the effective dose.

The survey design was carried out as recommended by Raggio [15] for epidemiological investigation. All parameters used in this approach is described in reference [16]. A confidence level of 95% and a statistical power of 80% were used to determine the sample size. The standard deviation of radon concentration of 64 Bq/m^3, a mean of 130 Bq/m^3, and an standard error of 13 Bq/m^3 were chosen based on parameters used in a similar study [17]. A non-response rate of 20% was also considered. Applying these criteria, 177 households in Andradas, 158 in Caldas, and 342 in Poços de Caldas were selected, totaling 677 households. The final analysis included only dwellings that produced four valid measurements, meaning valid readings for both the living room and bedroom, and were present in both survey campaigns. A total of 577 residences met these criteria, resulting in a total of 2,308 radon concentration measurements. It was assumed that a total of 1% of all residences within the area selected by the study would be evaluated, which equated to a more comprehensive value than any calculated sample number. This adopted percentual (1%) is greater than the used in surveys conducted in different countries [18].

For the fieldwork, technicians from the Municipal Health Secretaries were trained, including the installation of dosimeters, specifically agents from the Family Health Strategy or Dengue control teams of the three selected municipalities, namely: five agents from Poços de Caldas, fourteen from Caldas, and one hundred and sixteen from Andradas, who were supported by a supervisor. A handbook was elaborated specifically for this purpose. The work consisted of an initial approach, an interview about the characteristics of the residence, and the installation and retrieval of dosimeters. As dosimeters stay in the dwellings for long time, they were visited once every two months for quality control.

Four small dosimeters of semi-spherical shapes were installed, with a volume of the order of 13 cm^3, fixed at 1.5m from the floor on the walls of the living room (two) and one of the bedrooms (two), in each of the stages, called "campaigns" (spring-summer / October-winter). Those rooms are considered as the spaces where residents stay most of the time.

The dosimeter used is a passive type, consisting of a solid-state detector for nuclear track (SSNTD) enclosed by a diffusion chamber for radon. The detector is made of a polymer known by the trade name CR-39, which, when exposed to alpha radiation, undergoes damage to its microstructure. This atomic-scale damage is then magnified through a chemical treatment with KOH, allowing for visualization under an optical microscope.

The concentration of radon in the air is assessed using a calibration factor and the trace density obtained from the polymer analysis (traces/cm^2). The calibration factor was experimentally measured for each batch of plastic (CR-39). To accomplish this, at least three sets of detectors were exposed to known levels of radon concentration. The calibration factor averaged around 2.5 tracks/cm^2 per kBq·h/m^3. Additional details about this dosimeter can be found in [19].

Although thoron interference. in the measurements was not considered, it is known that its thoron relative sensitivity typical for this type of alpha track-etch detectors (no filter – closed diffusion chamber) is about 5% when compared with for radon [20]

The dosimeters (living room and bedroom) remained approximately 6 (six) months (spring-summer) in the households, were removed for analysis and replaced by two others and remained another 6 (six) months (autumn-winter), being withdrawn at the end of the period. The dosimeter analysis was performed by the Poços de Caldas Laboratory team that participates on International Radiation Measurement Laboratory Intercomparison Programs promoted by the UKHSA (United Kingdom Health Security Agency). The experimental uncertainty of the measurements of radon concentration using the detectors was estimated between 14.5% - 23.3%.

The radon concentration data were converted to radiation dose using the UNSCEAR approach [21] and calculated according to the Equation 1:

Eq. 1 $E = CRn_{222}.FO.FE.DCF$

E	is the effective dose (mSv/y);
CRn222	is the concentration of Rn222 (Bq/m^3);
FO	is the occupancy factor. Adopted value is 7.000 h per year;
FE	is the equilibrium factor. Adopted value is 0.4;
DCF	is the dose conversion factor. Adopted value is 9 (nSv/(Bq.h/m^3) [21].

2.1. Data analysis

The minor territorial piece was the census tract of the Brazilian Institute of Geography and Statistics - IBGE [14]. The results were grouped by municipality and within each municipality by urban and rural type. In all campaigns, analyses were performed considering the measurements of bedrooms and living rooms, both separately and in aggregate form.

Measures of central tendency (arithmetic mean, geometric mean, mode and median) per municipality and within each municipality by urban and rural type and dispersion (minimum and maximum values) were calculated. To obtain the equivalent dose the values of the arithmetic means (Bq/m^3) found were converted to dose (mSv/year). The calculation of the population-weighted dose can then be carried out based on the average dose per census tract, according to Equation 2 [21].

Eq 2. $C_p = \frac{\sum_{i=1}^{k} c_i.p_i}{\sum p_i}$

Where:

Cp is the concentration weighted by population (Bq/m^3);

ci is the mean radon concentration adopted for each census sector;

pi is the population of each census sector I;

i is the index of census sector;

k is the number of census tracts;

To identify the variables that could explain the found radon concentrations, a logistic regression was conducted with the dependent variable "radon concentrations ≥200 Bq/m^3" (yes, no) and the following independent variables: municipality (Andradas, Caldas, Poços de Caldas); type of area (rural, urban); construction age (before 1976, 1977-2000, after 2000); living room foundation (solid, suspended); bedroom foundation (solid, suspended); house base (supported by the ground, suspended, over a basement, or mixed); and nighttime window opening (yes - always, usually a few times, no - never). Each independent variable was individually evaluated with the response variable (maximum radon concentration ≥ 200 Bq/m^3 per dwelling) and tested for statistical significance using the chi-square test. The variables that presented p-value <0.05 were inserted and evaluated in a multivariate logistic regression model, to estimate the adjusted final model.

The type of bedrock underneath the bedroom and living room can influence radon concentrations indoors. Radon gas can enter buildings through cracks or gaps in the foundation, and the composition of the bedrock can affect the pathways through which radon migrates into the indoor environment.

Additionally, differences in construction materials and ventilation systems between the bedroom and living room can also contribute to variations in radon levels. Therefore, considering the type of foundation for each room separately allows researchers to assess its specific impact on radon concentrations and understand potential differences in exposure levels between living spaces.

2.2. About the cutoff point

In Brazil there is no official legislation regarding indoor radon. The World Health Organization- WHO recommends maintaining the arithmetic mean below to 100 Bq/m^3 and where it is not possible the maximum reference values should not exceed 300 Bq/m^3. In this study, the adoption of a cutoff point of 200 Bq/m^3 was adopted, considering the precautionary principle using an earlier ICRP (International Commission on Radiological Protection Statement on Radon), which indicated that levels between 200 and 400 Bq/m^3 categorized attention levels. The ICRP, IAEA and WHO recommend that each country adopt the reference level to radon gas that they deem relevant and effective [3, 22, 23], but not exceeding 300 Bq/m^3.

The descriptive and analytical statistical procedures were performed in Excel and SPSS software. Geographic coordinates for geoprocessing purposes were obtained through GPS.

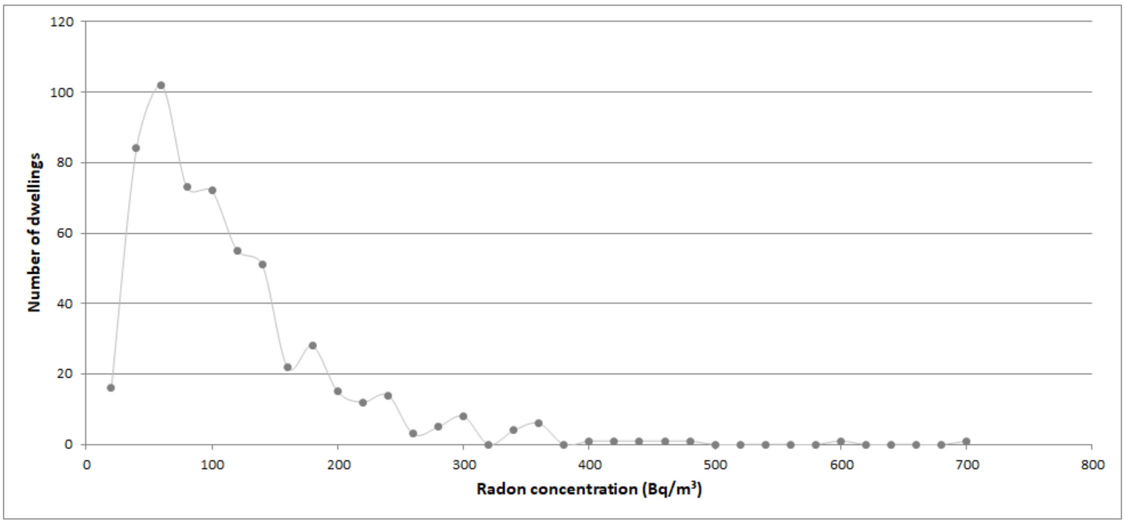
3. RESULTS AND DISCUSSIONS

Most (76%) of the radon concentrations presented in Figure 2 (mean by households considering the four measurements) were between 20 and 140 Bq/m^3, with the most probable value of 50 Bq/m^3 (mode). The lognormal distribution was the one that best represented the data set.

Figure 3 shows the box plot of the mean radon concentrations in the dwellings. It was observed that, in general, the medians of the rural areas were higher than the urban areas. This figure allows observing the extreme values found by municipality, all in the upper quartile, in particular, Caldas rural and Poços de Caldas urban.

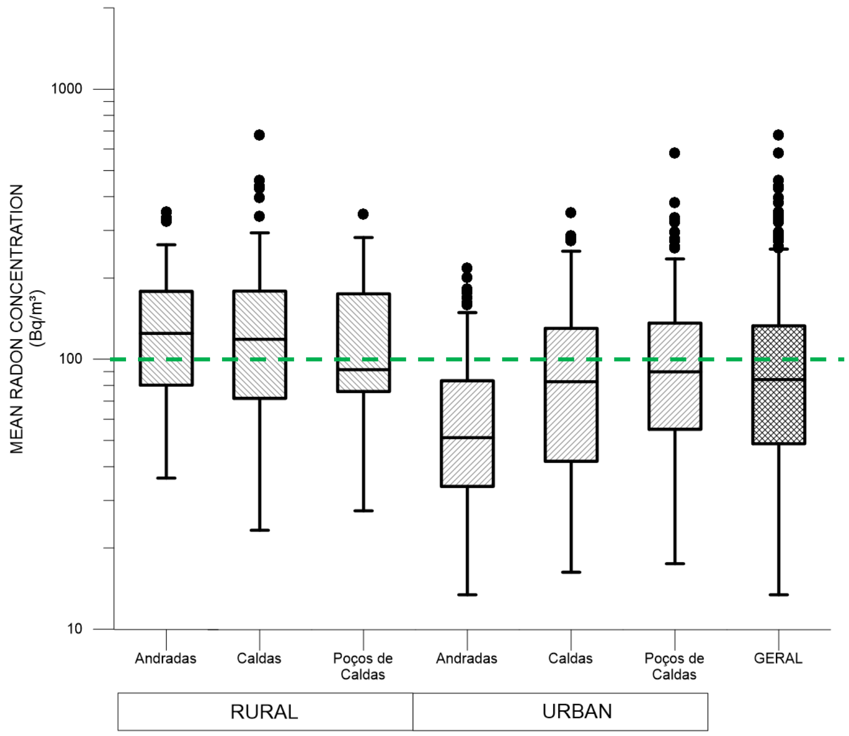
Table 1 presents the results of the radon concentrations, weighted by the population, and its respective effective dose. The arithmetic averages were 104.2 Bq/m^3 (unweighted by population), which means 2.63 mSv/y, and 100.9 Bq/m^3 (population weighted), which means 2.55 mSv/y. Geometric averages were 76.7 Bq/m^3 (unweighted by population), which means 1.94 mSv/y, and 89.7 Bq/m^3 (population weighted), which means 2.26 mSv/y. The rural area of the municipality of Caldas had the highest mean radon concentration (149.2 Bq/m^3 or 3.76 mSv/year) in relation to the others and also the maximum observed value 1,645 Bq/m^3. From the 577 dwellings evaluated, 123 have radon concentrations ≥200 Bq/m^3, observed more in rural than in urban areas (Table 1).

Figure 2: Frequency distribution of radon gas concentration (Bq/m3) in 577 dwellings.



The distribution of the characteristics of the households evaluated is described in Table 2, as well as the results of the adjusted final model. From the 7 (seven) variables selected, 5 (five) were maintained in the final model ($p<0.05$ in bivariate analysis), being associated to the maximum radon concentration ≥ 200 Bq/m^3 except for "living room foundation" and “house base”. The households located in the municipality of Caldas and Poços de Caldas have, respectively, 2.94 (95% CI 1.55-5.57) and 2.45 (95% CI 1.36-4.42) times more chance having concentration of radon ≥200Bq/m^3 when compared to the municipality of Andradas.

Figure 3: Box plot of the radon mean concentrations in dwellings classified by municipalities and geographic areas. A horizontal line at 100 Bq/m³ indicates the reference level recommended by the WHO.



Regarding the type of area, the dwellings located in the rural area are 2.26 (95% CI 1.35 - 3.79) times more likely to have a radon concentration ≥200 Bq/m^3 compared to those located in the urban area. Dwellings built before 1976 has a 2.35 (95% CI 1.35 - 4.06) times greater chance of hav-ing a radon concentration ≥200 Bq/m^3 compared to those built after the year 2000. Those built in 1977 to 2000 were not statistically associated with radon concentrations ≥200 Bq/m^3. Dwellings whose foundation is solid (non-suspended) had 2.57 (95% CI 1.39 - 4.75) times more likely to have radon concentrations ≥ 200 Bq/m^3. Regarding the variable room window open during night, dwellings that are not open in this period are 2.18 (95% CI 1.30 -3.66) times more likely to have a radon concentration ≥200 Bq/m^3 in relation to those that remain with the bedroom window open.

Table 1: Concentrations of radon (Bq/m3) and effective dose (mSv/year) weighted by the population.

Municipality	Area	N	Minimum and maximum valour (Bq/m³)[1]	Concentration (Bq/m³) weighted by population based		Effective dose (mSv/y)
				AM[2]	GM[2]	
Andradas	Rural	35	32.8-456.3	139.6	124.6	3.52
	Urban	125	8.4-255.5	68.0	59.0	1.71
Caldas	Rural	61	10.9-1.645.3	149.2	121.3	3.76
	Urban	69	7.2-515.6	80.6	66.0	2.03
Poços de Caldas	Rural	23	21.5-468.7	88.5	78.0	2.23
	Urban	264	9.1-767.6	106.2	95.9	2.68
All		577		100.9	89.7	2.55

[1] Minimum and maximum values are taken from all household measurements.

[2] Arithmetic Mean and Geometric Mean. Calculation of the radon concentration (Bq/m³) in households weighted by population was performed by municipality and type of area (urban or rural), based on the arithmetic and geometric means of each census tract, considering all housing measurements within the locality.

The spatial distribution of the measurements conducted in the municipalities is presented Figure 4, where four maps were constructed to facilitate the observation of points. From that, greater concentration of points is observed in the central areas that constitute the urban areas of the three municipalities, with greater population density, consequently greater number of dwellings, except in the municipality of Andradas. In that municipality there were no measurements with values ≥ 300 Bq/m³ in the urban area of this municipality, the highest value found being 255.5 Bq/m³. Figures 4a, 4b, 4c and 4c, show dwellings with maximum radon concentration ≤100 Bq/m³, >100 to <200 Bq/m³, ≥ 200 Bq/m³ to 300 Bq/m³ and >300 Bq/m³, respectively.

Table 2: Multivariate logistic regression between selected variables and radon concentrations > 200 Bq/m³.

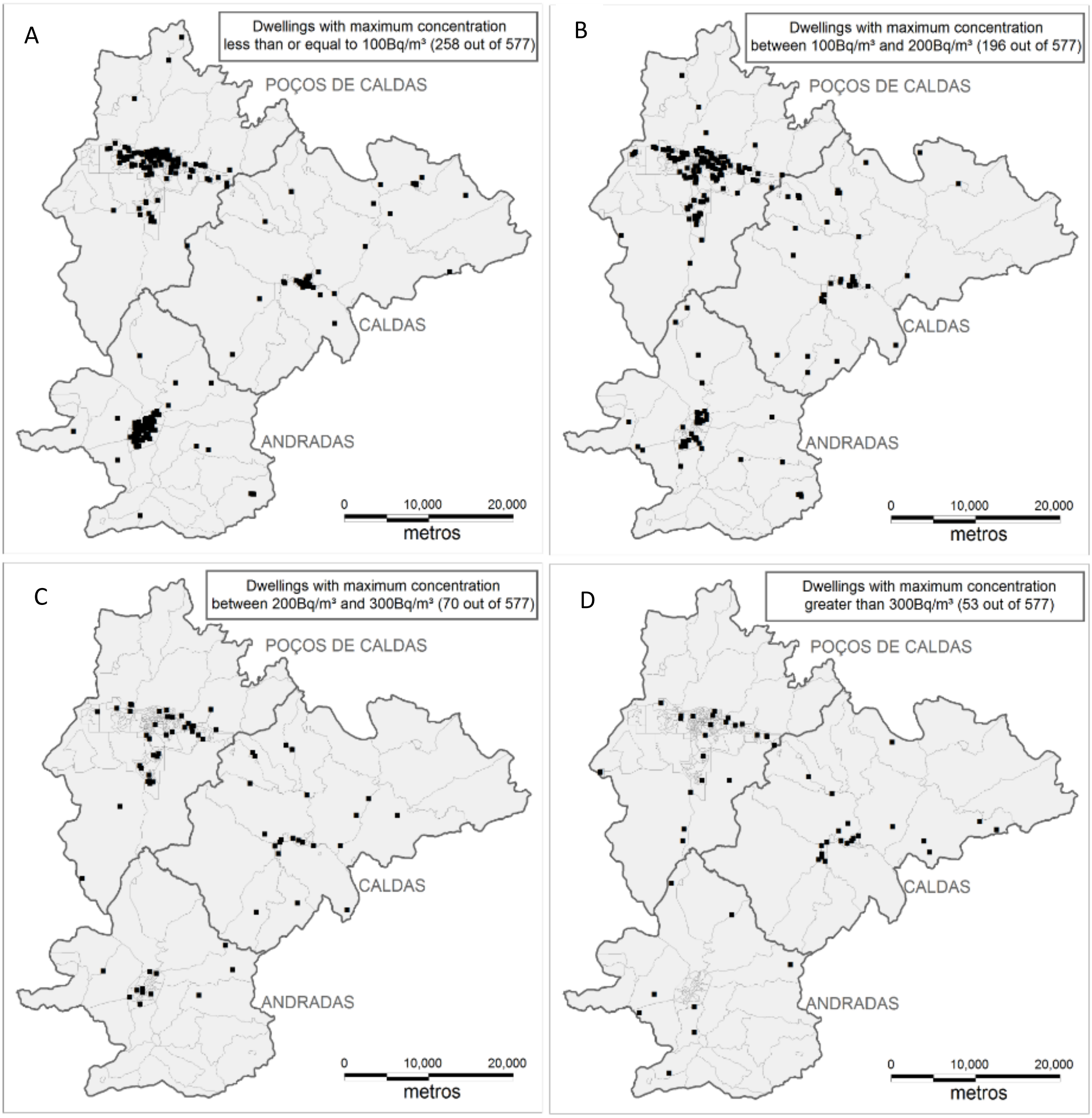
Selected variables	All dwellings	Odds ratio	Confidence interval 95%	p-value
Municipality				
Andradas	160	1		
Caldas	130	2.94	(1.55 – 5.57)	0.001
Poços de Caldas	287	2.45	(1.36 – 4.42)	0.003
Type of area				
Urban	458	1		
Rural	119	2.26	(1.35 – 3.79)	0.002
Time of construction of residence				
After 2000	131	1		
1977 - 2000	196	0.97	(0.59 – 1.60)	0.906
Before 1976	91	2.35	(1.35 – 4.06)	0.002
Bedroom foundation				
Suspended	126	1		
Solid	442	2.57	(1.39 – 4.75)	0.003
Bedroom window open at night				
Yes (always, usually a few times)	379	1		
No (never)	198	2.18	(1.30 – 3.66)	0.003

Missing values: Time of construction (159); Bedrock of bedroom (9).

As well as the increased risk of lung cancer due to occupational exposure to radon in miners, residential exposure in the general population should also result in an increased risk of lung cancer. In our analysi's unit consisting of households in urban and rural areas on municipalities of Andradas, Caldas and Poços de Caldas, 21.3% (123) of dwellings were found with at least one of the radon concentration measurements ≥200 Bq/m³. Using the reference level of 100 Bq/m³ recommended by the World Health Organization we found that 55.3% of households had at least one measurement higher than this value [3].

When compared to the reference value of 300 Bq/m³ recommended by the International Atomic Energy Agency (IAEA) [22] we found that 9.2% of households had higher concentrations. In addition, the arithmetic means of 104.2 Bq/m³ and 76.7 Bq/m³ and geometric values of 100.9 Bq/m³ and 89.7 Bq/m³, unweighted and population weighted, respectively, are above the UNSCEAR global mean values of 46 Bq/m³ (unweighted) and 30 Bq/m³ (weighted) [21].

Figure 4: Maps of indoor radon concentrations in the three selected municipalities, 2011-2012.



Comparing the results obtained in previous studies conducted in the same region, the arithmetic averages are notably higher than those reported by Amaral [8] at 204 Bq/m³ and by Veiga [24] at 220 Bq/m³, both in the rural area of Poços de Caldas. It is noteworthy that these same authors also documented maximum values of 1046 Bq/m³ [8] and 1024 Bq/m³ [24] in the rural area of Poços de Caldas, which are slightly lower than the 1645 Bq/m³ found in the present study.

It is important to highlight the comparative limitations between the previous studies conducted in the same region and our results, which are partly attributable to methodological differences, primarily related to the sampling coverage. The current study had a broader spatial coverage, encompassing both urban and rural areas of three municipalities, and a significantly higher number of measurements (2,308 measurements).

In other regions of the country, indoor radon measurements were also conducted, such as in Monte Alegre-PA [25], São Paulo-SP [26] and Campo Largo-PR [27], with arithmetic averages of 116, 131, and 186 Bq/m³, respectively. These values are also higher than the means found in this study. It is noteworthy that the arithmetic averages of indoor radon obtained in similar studies conducted in countries such as Canada (34 Bq/m³), China (44 Bq/m³), Denmark (59 Bq/m³), and Germany (50 Bq/m³) were well below 100 Bq/m³, despite higher maximum values (1720 Bq/m³, 596 Bq/m³, 1200 Bq/m³, and > 10,000 Bq/m³, respectively) [21].

When analyzing the characteristics of dwellings in search of possible explanations for these elevated values, we found an association with radon concentration levels ≥200 Bq/m³ among residences in the municipalities of Caldas and Poços de Caldas compared to residences in the municipality of Andradas. This may be due to the fact that in urban areas, a higher fraction of people living on higher floors, resulting in lower radon concentrations. We also observed this association between houses built before 1976 compared to those built after 2000, between those where the living room foundation is solid compared to suspended ones, and between dwellings where bedroom windows remain closed during the night compared to those that remain open.

The determinants for radon gas concentration indoors include the soil and geology upon which the house is built, the construction materials used, and the methods employed for heating and ventilation, as well as the presence of cracks in floors or solid walls, construction joints, cavities within walls, among other factors [28]. In a study conducted in Finland, similar results to ours were reported, observing higher levels of radon in solid or underground dwellings compared to suspended ones [29]. Similar findings were reported in Denmark [30]. Regarding the construction period of dwellings, Arvela also found elevated levels of radon in older buildings, which was also observed by Shendell and Carr in New Jersey for the years 2010-2011 [29, 31].

It is important to note that some dwellings were identified where residents kept the house closed at night, hindering the circulation of fresh air and the subsequent outflow of radon gas. Another factor that may reinforce this risky behavior is the influence of cold climates, which can lead people to keep their houses closed both at night and during the day [32]. Hence, radon levels can vary significantly, even among adjacent and similar houses, if only some relevant controlling factor is different [33].

Despite the results of this and other studies in Brazilian regions revealing high levels of radon in enclosed environments, exceeding the recommended levels by the World Health Organization, there are still no specific national laws defining a reference value for this radioactive element or establishing surveillance standards for both old and new homes. This situation leaves people vulnerable to potential health effects resulting from the inhalation of radon-222 [34, 35].

The International Agency for Research on Cancer classifies radon as a Category 1 carcinogen, indicating it is unequivocally known to cause human and animal cancers [36].

According to the World Health Organization [3], in a specific publication on indoor radon, 3-14% of lung cancer cases are attributed to this agent. Considering an incidence rate for this neoplasm estimated at 32,560 new cases in Brazil for each year of the triennium 2023-2025 [2], it can be expected that between 976 and 4,558 cases of lung cancer may occur this year attributable to radon, with 541-2,523 cases in men and 436-2,596 cases in women.

As none of these towns (Poços de Caldas, Andradas and Caldas) included in the study had records of population-based cancer during this study, it was not possible to assess a higher or lower number of cancer cases compared to other regions with similar conditions. However, in 2007, an epidemiological investigation study was conducted to assess the role of radiation and other risk factors for certain types of cancer in several cities in southern Minas Gerais, Brazil [12]. The city of Andradas was considered a high-priority area for lung cancer in men and liver cancer in women. Similarly, the region of Poços de Caldas was considered an important site for leukemia cases in both men and women.

A study carried out in this region of Minas Gerais to assess the pattern of cancer mortality in some Brazilian regions said to have high natural radioactivity shows that in the municipality of Poços cancer mortality is higher than could be expected, based on reference population. Likewise, in the municipality of Poços de Caldas, there was a significant increase in mortality from stomach, lung, breast and leukemia cancer [37].

Concurrently, at the onset of the Research Project on indoor radon levels in three municipalities of the Poços de Caldas Plateau, the Population Base Cancer Registry was established and implemented by the Municipal Health Secretariat of Poços de Caldas, with support from the Evaluation and Surveillance of the Minas Gerais State Health Secretariat. The objective was to elucidate the actual quantity of cancer cases in the region, given that Poços de Caldas hosts a Center of High Complexity in Oncology (CACON) [16].

In a prior study, the coordinating group of the project conducted an analysis of the cancer mortality pattern in the locality and observed excess lung cancer deaths in Poços de Caldas (SMR = 147, 95% CI 106-188) and in Andradas (SMR = 208) [12]. However, with consolidated results from a 5-year investigation period for new cases (2010-2014), including active searches in all sources such as hospitals and laboratories, it was observed that the pattern does not deviate from the national scenario related to lung cancer. There were recorded 73 cases in men and 49 cases in women, ranking 4th and 5th, respectively, in the list of main primary cancer sites in Poços de Caldas [38].

This information should not downplay the necessity for research and the development of strate-gies to monitor population health and radon levels in both old (mitigation) and new (prevention) dwellings, as recommended by the World Health Organization [33]. There are several challenges in conducting research on health effects related to chronic low-dose exposure, as well as in performing case-control or cohort-type analytical studies in small populations. Such studies require prolonged periods of observation to accumulate enough individuals to achieve statistical power. In these inves-tigations, the need to evaluate individual doses for everyone and to control and distinguish potential biases and confounding factors should be considered [10].

The solution to these challenges, as suggested by Cardis 2005 [39], would be the implementation of a multicenter study. This type of study involves the participation of different populations residing in areas with high levels of natural radioactivity and may exhibit different demographic, socioeconomic, and environmental characteristics, which would allow for the collection of data from a more diverse and representative sample, thereby increasing the validity and generalizability of the results obtained. Additionally, this type of study enables the comparison between different populations and the identification of patterns or trends that may not be observed in studies conducted in a single locality. The use of common protocols for dosimetry and epidemiological design would enable direct result comparisons and combined analyses, maximizing the information derived from these studies [39].

It is essential to engage the public about the potential risks associated with exposure to radon in enclosed environments [39]. This is a challenging task, as this information in the population is often limited. As a preventive measure, in this investigation a basic manual was created to inform residents about radon and guide them to ventilate their homes (keeping doors and windows open during the day, mainly) to reduce indoor radon levels [40]. Additionally, as a surveillance tool, it is recommended to assess radon levels in the soil before new constructions, a practice proven to be effective in various parts of the world with exposure standards like or higher than those observed in the municipalities of the Poços de Caldas Plateau [30, 39].

4. CONCLUSIONS

In our findings, we have observed indoor radon levels surpassing the cut-off point specified for this study (≥200 Bq/m^3), with over half of the households recording at least one measurement exceeding the value recommended by the World Health Organization (100 Bq/m^3). We also observed that some dwellings characteristics (rural areas, older, solid foundation) as well as residents' habits (sleeping with closed windows) may contribute to elevated indoor radon levels.

The Project team recommends that multicenter, analytical-type epidemiological studies to assess the association between exposure and potential radon-induced cancers, as well as to implement specific national legislation that stipulates national parameters reference values for exposure to indoor radon. Recommendations for measures to reduce exposure in new constructions should be elaborated, based on international experiences. It is highly recommended that both the Poços de Caldas Population-Based Cancer Registry (RCBP) and the Minas Gerais State Health Secretariat continue their vigilance in monitoring new cases of cancer within this region.

ACKNOWLEDGMENT

We would like to extend our sincere gratitude to the teams of the Cancer Surveillance and Assessment Program of State Health Department, the Poços de Caldas Laboratory (LAPOC/CNEN) and the Technical Area Environment, Work and Cancer of the Coordination of Prevention and Surveillance (Conprev/INCA) for their technical support during the whole of investigation. To the Pan American Health Organization (PAHO) for their invaluable support and collaboration in the implementation of the TC54 cooperation agreement. Their dedication and commitment have significantly contributed to the advancement of our research efforts and the promotion of public health initiatives.

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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