BJRS

BRAZILIAN JOURNAL OF RADIATION SCIENCES
09-02 (2021) 01-18

SBPR
Sociedade Brasileira de Proteção Radiológica

# Indoor radon assessment in kindergartens: a step towards a national action plan

Dias[a-b] D.C.S., da Silva[a] N.C., Silva[b] W.L., Rodrigues[c], M.V.

[a] *Brazilian Commission for Nuclear Energy/Poços de Caldas Laboratory/Radon Dept, 37719-005, Poços de Caldas, MG, Brazil*

[b] *Universidade Estadual de Campinas/Geosciences Institute, 13083-970, Campinas, SP, Brazil*

[c] *Universidade Federal de Alfenas/Science and Technology Institute, 37715-400, Poços de Caldas, MG, Brazil*

*danilacdias@gmail.com*

## ABSTRACT

**The study presents the results of indoor radon monitoring of 342 Public Kindergarten/Childcare Unit (CEI) rooms of a Brazilian municipality within a region featuring high natural radioactivity. Facility characterization and local perception assessment were also conducted. Rooms were monitored by exposing CR-39 Nuclear Track Detectors for 356 days. Monitoring resulted in arithmetic and geometrical means of 83 and 61 Bq $m^{-3}$ respectively. Concentrations ranged between < 6 and 697 Bq $m^{-3}$ while 2.6% of rooms from 4 CEI units presented values above 300 Bq $m^{-3}$, where similarities in construction materials used in the buildings were noted. High variability in radon concentration values was observed among regions, CEI units within a region and even rooms within the same building. Radon awareness campaigns conducted in the units revealed the need to improve stakeholder involvement between the scientific community and the public – essential in projects related to radiation protection. The first indoor radon monitoring study of children facilities in Brazil represents a step towards the adoption of a radon action plan, a national effort that must consider the environmental, geological and social diversities and challenges of a large and populous country. A program of such dimension should benefit from pilot studies as opportunities to gather experience in the different phases related to monitoring, logistics and society engagement. It is also clear that a national plan can only be successfully implemented by joint efforts from the scientific community, local and national authorities and an educated and engaged public.**

*Keywords:* **indoor radon, kindergarten monitoring, radon action plan, SSNTD technique, stakeholder involvement.**

ISSN: 2319-0612
Accepted : 2021-04-26

## 1. INTRODUCTION

Radon gas ($^{222}Rn$) is a decay product of uranium and a significant source of natural radiation, contributing significantly to human exposure as a relevant share of annual dose. Presenting half-life of 3.82 days, radon is found in indoor environments as it may penetrate buildings through faults and fractures and reach high concentrations [1]. Epidemiological studies conducted in North America, Europe and Asia provide strong evidence of the association between inhalation of high concentrations of radon and increased risk of lung cancer development, rendering chronic radon exposure as the second leading cause of the disease among smokers and the leading one among nonsmokers [2].

Recognizing the relevance of this radionuclide in the scope of natural radiation, the International Commission on Radiological Protection (ICRP) recommends countries to establish their own indoor radon reference levels [3]. In addition, authorities such as the World Health Organization (WHO) and International Atomic Energy Agency (IAEA) advise the implementation of control actions against public exposure to radon through the adoption of national action plans, which comprise extensive monitoring campaigns. It is noted they should prioritize human indoors living environments with high occupancy such as dwellings, schools and work environments [2,4].

In addition to the numerous efforts observed in assessments of radon concentration in homes, concerns with other environments such as schools grow rapidly. The United States have been monitoring school environments on a national level since the 1990s, while many recent studies on radon monitoring in kindergartens and schools have been observed in several European countries, among others the Czech Republic, Serbia, Republic of Srpska and Italy [5-8]. It is also noteworthy that extra attention should be given to young children when it comes to ionizing radiation exposure. In addition to presenting faster breathing rates (elevating the estimation of effective dose equivalent [9] and higher life expectancy (longer latent period for manifestation of potential health effects [10]), kindergarten aged children may spend long daily hours in childcare/school facilities, having their exposure period increased [2,11].

Countries of great dimensions with environmental, geological and social diversity such as Brazil may face several challenges when it comes to national radon control efforts. In addition to a potentially high heterogeneity of radon concentrations found indoors, mapping of large areas calls for a comprehensive system of survey design, logistics, dosimetry, quality control of processes and public engagement that take into account all the diversities referred above. In that sense, small scale studies are solid opportunities for experience gathering in different phases and strategies essential to a national plan [12].

Public Kindergarten/Childcare Units (CEI) in Brazil may be particularly interesting candidates for indoor radon studies. These are places Brazilian children (ages 0-5) attend regularly throughout the year, spending up to 10-11 hours daily [11]. As public institutions distributed all over the country, they would also allow the acquiring of experience – essential to conduct large scale monitoring campaigns – while considering particularities of different regions. Finally, they would make strong targets for advances in stakeholder engagement through the involvement of local communities.

Regulation applicable to radon exposure is contemplated in the National Basic Standard for Radiation Protection [13], prescribed by the Brazilian Commission for Nuclear Energy. The legislation still applies the ICRP 60 approach [14] comprising practice and intervention exposure situations. For practices, 1 mSv/year and 20 mSv/year [13] are defined as the dose limits for the public and workers, respectively. 10 mSv/year [15] is defined as the generic intervention level for chronic exposure from natural radiation sources such as the ones arising from the use of building materials containing uranium and thorium and from natural radionuclides present in soil at higher levels. As far as radon dose conversion is concerned, the current Brazilian legislation still applies ICRP 65 [16], i.e. 5 mSv/year per WLM for workplaces [17] and 4 mSv/year per WLM for dwellings [18]. In both cases 0.4 is prescribed as the equilibrium factor. The occupancy factors for workplaces and dwellings are defined as 2000 h and 7000 h respectively [17,18].

While the reference level of 1000 Bq/m$^3$ is defined for mitigation/remediation actions in places like underground mines and indoor workplaces [19], Brazil has yet to establish reference levels of indoor radon concentrations in dwellings. In that sense, collection of data from different regions would not only advance the country towards the definition of such references but would also represent another step towards a successful national action plan.

The objective of the study was to conduct a 1-year radon monitoring program of Public Kindergarten/Childcare Units (CEI) of Poços de Caldas (Brazil), including physical and social characterization of target facilities and local staff communication through radon awareness campaigns and open discussions.

The Brazilian municipality of Poços de Caldas is located in the Southeastern region of Minas Gerais State, bordering the State of São Paulo. Covering a territory of 547 $km^2$, the city sits in a plateau region of altitude at 1246 m ASL and mild climate, while reaching an average temperature of 18° C and annual rainfall of 1745 mm [20].

The area's geology is characterized by a 35 km diameter alkaline intrusion of volcanic nature containing mineral occurrences such as uranium-zirconium, thorium-rare earths and uranium-molybdenum associations [21]. Moreover, the region – which is world-renowned for its radioactive anomalies [22] – hosts the first Brazilian uranium mine site, currently under closure stage [23].

With a population of 166K inhabitants [24], the city presents a Municipal Human Development index value above the national Brazilian average [25]. The local public early childhood education system is composed of 45 childcare/kindergarten units (CEI), which serve children ages 0 to 5 years old. The units are distributed throughout the urban region of Poços de Caldas and run all year (with short periods of recess in July and January), on Monday-Friday from 7:00 to 6:00 pm. The system currently attends 5800 children and employs 1100 caretakers and educators [11,26].

## 2. MATERIALS AND METHODS

### 2.1. Sampling and exposure

The study covered all public CEI units of Poços de Caldas, as indicated by Figure 1. The targets at each unit were rooms occupied by children throughout the day (classrooms and common indoor spaces such as media and playrooms). The number of rooms per CEI unit ranged from 3 to 20, with an average of 8 rooms per unit. A dosimeter was installed in each of 377 rooms monitored for an average exposure period of 356 days. The devices were attached on the external walls of metal cabinets inside rooms, at heights of 1.5-2.5 m.

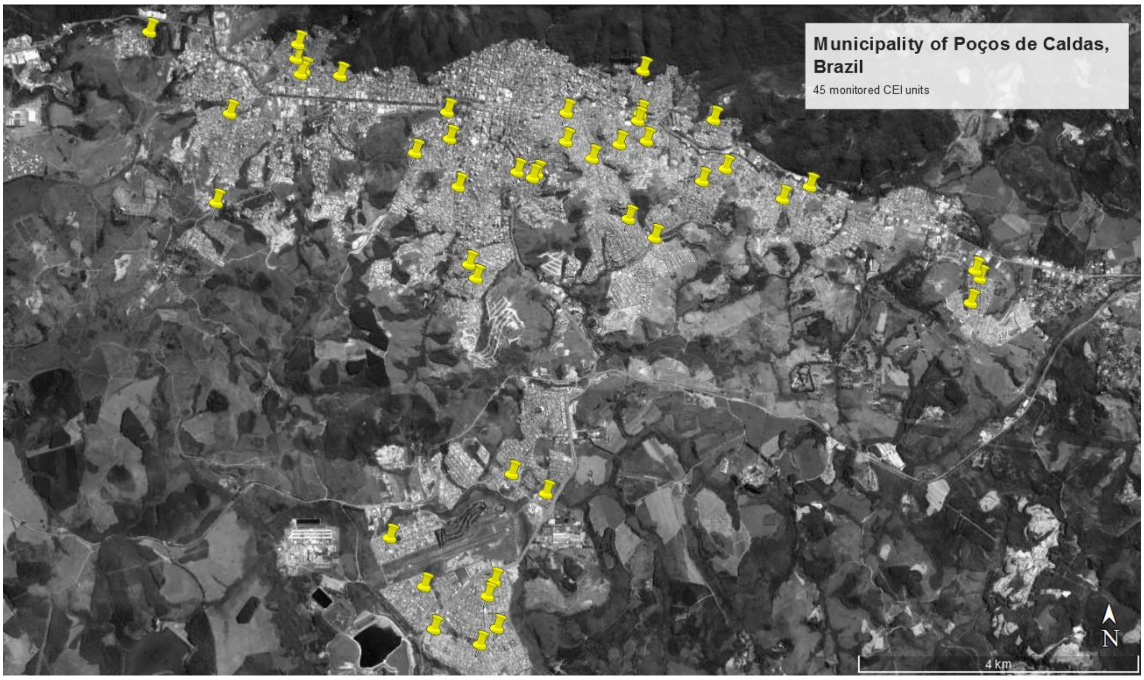


**Figure 1**: *Public CEI units distributed on the city.*

The process of dosimeter installation was accompanied by individual visits to each CEI, during which the goals of the program were elucidated to unit coordinators. Information regarding the buildings were also collected such as types of building materials on floors and walls, foundation type, number of stories, age of building and presence of faults and cracks in addition to ventilation habits and school routine aspects (permanence indoors).

### 2.2. Detector preparation, post-exposure treatment and analysis

The technique based on Solid State Nuclear Track Detectors (SSNTD) was applied in the study with the use of CR-39 Nuclear Track Detectors (25 mm x 25 mm and thickness of 1.5 mm). The dosimeters exposed in CEI units were sets composed by a CR-39 contained in a diffusion chamber that enables the gas to reach its interior (Figure 2).


**Figure 2**: *Passive radon measurement devices composed of diffusion chamber and CR-39 detector.*

Preparation and assembly of detectors as well as its analysis and interpretation of results were conducted following QA/QC practices established by the Quality Management System (QMS) of Poços de Caldas Laboratory (LAPOC) – accredited under Standard ISO/IEC 17025:2017. Quality assessment of the SSNTD technique adopted by LAPOC is continuous process composed of two complementary approaches – based on statistical studies of the parameters of accuracy (comprised of precision and trueness), method robustness, linearity of response, detection limit, work range and measurement uncertainty; and on annual participation in an international intercomparison exercise of radon passive detectors [27].

Dosimeters were prepared and assembled in laboratory up to 24 hours prior to installation. This stage consisted in an antistatic treatment of CR-39 detectors [28], followed by assembly and packaging.

Upon return after the exposure period, detectors were etched in a 6.25 M sodium hydroxide solution per 60 minutes at 98° C. Etching neutralization was achieved with a 2% acetic acid solution immersion, followed by drying and immediate analysis.

CR-39 analysis was conducted in an automated alpha track reading system (TASL), composed of a x-y-z table and a Nikon camera-mounted optical microscope capturing 300 images from each detector along an area of 221 mm$^2$ [28]. Upon detecting an event, it evaluates a series of physical parameters such as track dimension (minor and maximum projected axis), symmetry, convexity, sharpness, contrast and grayscale in order to identify count alpha particle tracks. Using a conversion factor of 0.52 (determined by TASL and controlled by the laboratory through participation in annual intercomparison exercises) [27] and the given exposure time, the system provides average radon concentrations (Bq $m^{-3}$) [28]. The combined standard uncertainty of individual results presented by the track analysis system is expressed in terms of the overall variance and estimated considering: i) repeatability of measurements; ii) random error on track count (described by a Poisson distribution); and iii) reproducibility between CR-39 detectors (related to the quality variation among detectors as well as to their fading effect (loss of sensitivity) [28].

## 3. RESULTS AND DISCUSSION

The study, involving exposure of 377 dosimeters, achieved a 91% return rate (342 dosimeters), similarly to results observed in other school monitoring projects such as in Italy at 86% [8] and 96% [6]. It is noteworthy that even with an in-person return procedure conducted by the lab, devices were lost (during exposure) – an aspect that must be watched carefully in large scale projects. The monitoring effort, which covers indoor environments occupied by an average of 18 children per room, represents 3.5 % of the local population.

The arithmetic mean concentration observed was 83 Bq $m^{-3}$ ($\sigma$ = 79 Bq $m^{-3}$), with median value at 61 Bq.$m^{-3}$ and sample minimum and maximum of < 6 and 697 Bq.$m^{-3}$ respectively (Table 1). Such values correspond to an exposure range of 52 - 5955 kBq.$m^{-3}$.h for an average period of 356 days. Considering the remarkably low result of < 6 Bq $m^{-3}$ observed in one of the 342 evaluated rooms, it is important to leave a note regarding the track analysis system's detection limit. Final value estimation of this parameter was based on a comparative study considering approaches such as the Currie method for radioanalytical techniques [29] and the one recommended by BSI ISO 11665-4:2012 - Measurement of radioactivity in the environment. Air: radon-222 [30]. Based on an evaluation of factors considered in each approach, the latter was selected as the laboratory' LOD estimation method, whose application resulted in 6 Bq $m^{-3}$ for 1-year exposure.

**Table 1**: Descriptive statistics of indoor radon measurements in 342 rooms of CEI units.

| | **Min** | **Median** | **Max** | **Mean** | [2]**SD** |
|---|---|---|---|---|---|
| [1]$C_{Rn}$ (Bq $m^{-3}$) | < 6 | 61 | 697 | 83 | 79 |

[1]CRn-radon concentration; [2]SD-standard deviation

The geometric mean was calculated, resulting in 61 Bq $m^{-3}$ ($\sigma = 2$). A geometric mean of 77 Bq $m^{-3}$ ($\sigma = 2$ ) has been reported in the urban region of Poços de Caldas in residential measurements [31] while United Nations Scientific Committee on the Effects of Atomic Radiation estimates a worldwide geometric mean of 25 Bq $m^{-3}$ [1]. Table 2 presents the summary of results of both estimates.

**Table 2**: Summary of result estimation approaches applied for indoor radon determination.

| | **AM** | **SD** | **GM** | ***GSD** |
|---|---|---|---|---|
| $C_{Rn}$ (Bq $m^{-3}$) | 83 | 79 | 61 | 2 |

CRn –radon concentration; AM-arithmetic mean; SD-standard deviation; GM-geometrical mean; GSD-geometrical standard deviation (*dimensionless).

The distribution of radon concentration values observed in 356 days is presented by Figure 3. According to it, 24.6% of measurements carried out resulted in radon concentrations above 100 Bq $m^{-3}$ – reference limit advised by WHO, while 2.6% were above 300 Bq $m^{-3}$ – a threshold recommended not to be exceeded [2].

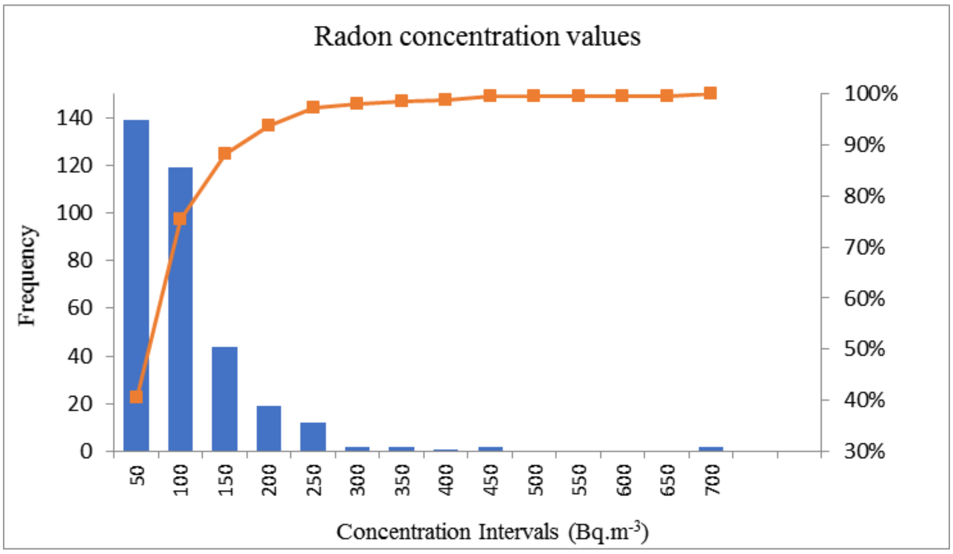


**Figure 3**: *Histogram of radon concentration ranges observed in 342 rooms of 45 CEI units of Poços de Caldas*

The distribution above suggests a lognormal behavior – indicating most of the exposure values come from lower concentrations, as it frequently happens [32]. Recent examples have been observed in dwellings in Brazil [31] and Canada [33], as well as in schools in South Korea [34].

The range of values and high standard deviation point to high variability of concentrations within the studied region, which are commonplace in many countries [32]. Similar monitoring efforts in school environments have elicited comparable estimates, ranging from 99 Bq $m^{-3}$ [7] and 119 Bq $m^{-3}$ [6], to higher means such as 176 Bq $m^{-3}$ [8]. Older indoor studies conducted locally employing the SSNTD technique provide similar values such as arithmetic mean 61 Bq $m^{-3}$ in residences and maximum value of 920 Bq $m^{-3}$ [21], indicating the persistence of high variability.

Mean values per each of 45 CEI units we also calculated, as presented by Table 3.

**Table 3**: Sample size (n) and radon concentration arithmetic means (AM) by CEI unit, accompanied by standard deviation (SD) and minimum and maximum values, all in Bq $m^{-3}$.

| **Mean values by each of 45 CEI units (in Bq $m^{-3}$)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **CEI Unit** | **(n)** | **AM** | **SD** | **Min** | **Max** | **CEI Unit** | **(n)** | **AM** | **SD** | **Min** | **Max** |
| S1 | 12 | 184 | 118 | 27 | 416 | C24 | 7 | 61 | 35 | 24 | 130 |
| S2 | 7 | 46 | 27 | 26 | 106 | L25 | 6 | 75 | 27 | 36 | 113 |
| S3 | 7 | 97 | 40 | 65 | 171 | L26 | 19 | 76 | 73 | 22 | 325 |
| S4 | 3 | 25 | 1 | 24 | 26 | L27 | 3 | 35 | 4 | 31 | 38 |
| S5 | 9 | 51 | 12 | 36 | 73 | L28 | 7 | 58 | 23 | 32 | 91 |
| S6 | 11 | 77 | 33 | 50 | 148 | L29 | 4 | 66 | 18 | 59 | 99 |
| S7 | 6 | 137 | 43 | 79 | 211 | L30 | 5 | 98 | 10 | 88 | 113 |
| S8 | 10 | 36 | 9 | 21 | 52 | L31 | 12 | 240 | 165 | 106 | 697 |
| S9 | 11 | 213 | 176 | 74 | 690 | L32 | 6 | 75 | 38 | 26 | 139 |
| C10 | 8 | 21 | 13 | 10 | 40 | L33 | 9 | 59 | 18 | 40 | 87 |
| C11 | 8 | 34 | 13 | 21 | 63 | L34 | 7 | 55 | 32 | 21 | 111 |
| C12 | 8 | 91 | 52 | 39 | 169 | L35 | 3 | 69 | 84 | 32 | 198 |
| C13 | 8 | 161 | 63 | 68 | 244 | L36 | 11 | 120 | 40 | 76 | 216 |
| C14 | 7 | 23 | 14 | 1 | 43 | O37 | 5 | 80 | 45 | 32 | 141 |
| C15 | 6 | 37 | 26 | 29 | 98 | O38 | 9 | 43 | 16 | 24 | 76 |
| C16 | 9 | 59 | 64 | 14 | 172 | O39 | 12 | 36 | 12 | 25 | 60 |
| C17 | 7 | 76 | 35 | 41 | 144 | O40 | 6 | 69 | 13 | 59 | 94 |
| C18 | 11 | 38 | 21 | 19 | 96 | O41 | 7 | 46 | 28 | 26 | 110 |
| C19 | 7 | 96 | 32 | 56 | 130 | O42 | 4 | 35 | 5 | 30 | 41 |
| C20 | 9 | 50 | 34 | 3 | 107 | O43 | 10 | 78 | 17 | 54 | 107 |
| C21 | 5 | 45 | 10 | 41 | 65 | O44 | 6 | 34 | 8 | 26 | 46 |
| C22 | 3 | 53 | 26 | 31 | 81 | O45 | 7 | 118 | 62 | 57 | 235 |
| C23 | 5 | 94 | 16 | 79 | 118 | | | | | | |

The results above indicate high dispersion of mean concentrations among the 45 CEI units, ranging from 21 to 240 Bq $m^{-3}$. While 16% of the units presented arithmetic mean concentration above 100 Bq $m^{-3}$, 42% of the units presented at least one room over that reference value (Figure 4).

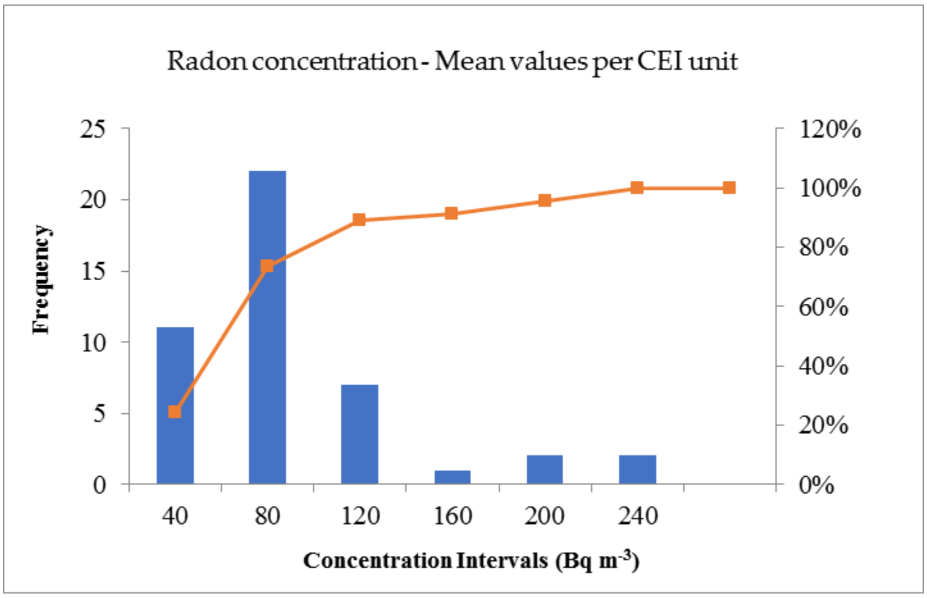


**Figure 4**: *Distribution of mean results among CEI units*

Finally, an evaluation of the data distribution observed in each CEI unit, as well as relations among them, is presented through a box plot analysis on Figure 5.

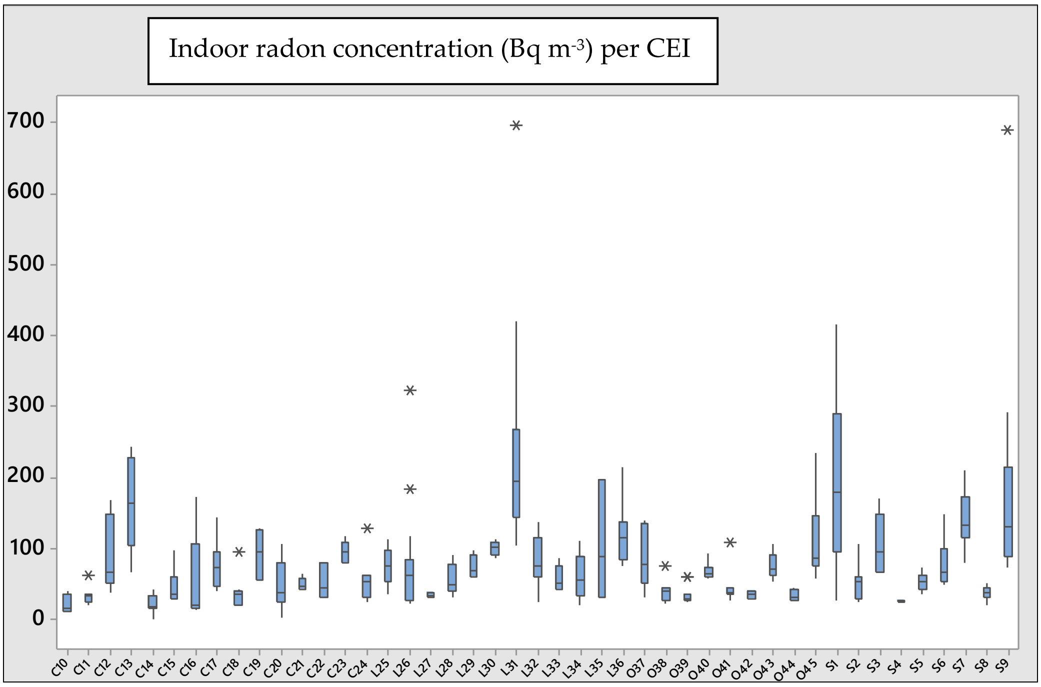


**Figure 5**: *Box plot analysis of indoor radon concentrations at CEI units.*

Again, the assessment above demonstrates high dispersion of results – this time among units – noticeable in the comparison among medians and quartiles. When regions C (Center/downtown), L (East), O (West) and S (South) within the municipality are evaluated separately, the wide variation of results still stands. Furthermore, the box plot evaluation points to the presence of 10 outliers found above maximum limits of distribution, observed in the 4 regions.

An additional estimate of suspicious values was performed through a Grubbs test, which pointed to the presence of 12 outliers in the data set, matching 8 out of the 10 outlying values elucidated by the box plot. Half of the outliers exceed 100 Bq $m^{-3}$ and should be further investigated in follow-up studies.

On construction aspects, the buildings display quite similar structures (predominantly one-story buildings leveled on ground floor; masonry walls and concrete slab roofs) while construction materials used on floors varied highly – in sequence of predominance: ceramic tiles (37%); granilite (22%) (a composition of granite, marble, sand, cement and water); vulcanized rubber (21%); cement (15%); wood carpet (3%) and parquet (2%).

A closer look was taken upon the 9 highest radon concentrations found (> 300 Bq $m^{-3}$ values observed – equivalent to 2.6% of the monitored rooms). Distributed among 4 different units in 2 regions of the city, these ground floor and basement rooms share recent building construction ages (2002-2014), absence of apparent faults and cracks and granilite and ceramic tile floors (which suggests the role of these materials on the presence of radon) [35-37].

In addition to indoor radon monitoring, radon awareness campaigns involving CEI unit staff were conducted throughout the exposure year, when all units were offered the opportunity to welcome the authors in an informal gathering of all caretakers/educators. This activity of 30-45 minutes comprised of a presentation covering information on natural radiation, indoor radon and the project’s purpose. A general discussion followed involving all staff. The efforts achieved a positive response of 26%, translating into 12 units (out of 45) interested in the event (as CEI coordinators were free to decline the campaign visits). Meetings at each welcoming unit reached groups of 14 teachers/caretakers on average. All people involved were females – as male professionals at this educational level are practically nonexistent in Brazil (with very few acting as CEI coordinators). The activity represented an opportunity for risk perception assessment associated to radon. While a positive educational outcome was observed, expressed by the high interest on the theme and optimistic reaction displayed when concepts were demystified (such as the different sources of radiation naturally and artificially present in everyday life), the events pointed out a wide range of misconceptions related to radioactivity. Free association between the anomalous conditions of the city (perceived as “a very radioactive place”) and local incidence of cancer (also perceived as high by the public) was the most consolidated concern among participants.

## 4. CONCLUSION

Monitoring 342 rooms of 45 Public Kindergarten/Childcare Units (CEI) at the Poços de Caldas-Brazil resulted in arithmetic and geometric means of 83 Bq $m^{-3}$ and 61 Bq $m^{-3}$ respectively. Concentrations ranged from < 6 to 697 Bq $m^{-3}$ for an average exposure period of 356 days. Although 16% of units presented a mean value above the recommended reference of 100 Bq $m^{-3}$, 42% of the CEI units displayed at least one room over that concentration, recommended by WHO as a reference limit. Results point to high dispersion of indoor concentrations among the 4 urban regions assessed, as well as among units within a region and even within rooms of the same building. Concerning individual rooms monitored, 2% presented concentrations above 300 Bq $m^{-3}$ (in 4 units), where similarities in construction materials used in floors were noted. While low mean values (under 100 Bq $m^{-3}$) dominated the assessment, close attention should be given to environments such as childcare/kindergartens, which Brazilian children may occupy for 11 hours daily. As radon behavior indoors is associated to a range of combined factors, even tropical countries should not be underestimated. To further investigate the region and the role of different environmental and physical parameters in radon concentrations, assessments of terrestrial gamma, geogenic radon potential and room ventilation could be added to such study, especially in a region featuring higher levels of natural radiation.

The experience of conducting awareness campaigns revealed an urgent need to promote closer stakeholder involvement between the scientific community and the public, as the lack of education in the themes of radioactivity allows misconceptions, fueling unfounded fears of all activities related to nuclear science and technology and even preventing the establishment of citizen science initiatives – which can be vital in large scale projects.

The very first indoor radon monitoring study of children facilities in Brazil represents an important step towards the adoption of a radon action plan – a national effort that must consider the particularities of a continental size country of 211 million people. A program of such dimension should benefit from pilot studies as opportunities to gain experience in the different challenges related to monitoring, logistics and society engagement. It is also clear that a national plan can only be successfully implemented by joint efforts from the scientific community, local and national authorities and an educated public as part of the process.

## ACKNOWLEDGMENT

Authors are thankful for support from *Brazilian Commission for Nuclear Energy* (CNEN and *Coordination for the Improvement of Higher Education Personnel* (CAPES).

## REFERENCES

[1] UNSCEAR - United Nations Scientific Committee on the Effects of Atomic Radiation. **Sources and effects of ionizing radiation, report to the general assembly with scientific annexes**, New York: United Nations, 2008. 24p.

[2] WHO - World Health Organization. **WHO Handbook on Indoor Radon: A Public Health Perspective**, Geneva: WHO: 2009. 110p.

[3] ICRP - International Commission on Radiation Protection. **Radiological Protection Against Radon Exposure. ICRP 126**, New York: ICRP, 2014. 73p.

[4] IAEA - International Atomic Energy Agency. **Protection of the Public against Exposure Indoors due to Radon and Other Natural Sources of Radiation. Safety Standards: Specific Safety Guide-No. SSG-32**, Vienna: IAEA, 2015. 90p.

[5] FOTÍKOVA, I.; NAVRÁTILOVÁ ROVENSKÁ, K. Methodology for measurement in schools and kindergartens: Experiences. **Radiat Prot Dosim**, v. 164 (4), p. 612-617, 2015.

[6] BOCHICCHIO, F.; ŽUNIĆ, Z.S.; CARPENTIERI, C.; ANTIGNANI, S.; VENOSO, G.: CARELLI, V.; CORDEDDA, C.; VESELINOVIĆ, N.; TOLLEFSEN, T,; BOSSEW, P. Radon

in indoor air of primary schools: a systematic survey to evaluate factors affecting radon concentration levels and their variability. **Indoor Air**, v. 24 (3), p. 315-316, 2013.

[7] ĆURGUZ, Z,; STOJANOVSKA, Z.; ŽUNIĆ, Z.S.; KOLARŽ, P.; ISCHIKAWA, T.; OMORI, Y.; MISHRA, R.; SAPRA, B.K.; VAUPOTIČ, J.; UJIĆ, P.; BOSSEW, P. Long-term measurements of radon, thoron and their airborne progeny in 25 schools in Republic of Srpska. **J Environ Radioactiv**, v. 148, p. 163-169, 2015.

[8] TREVISI, R.; LEONARDI, F.; SIMEONI, C.; TONNARINI, S.; VESCHETTI, M. Indoor radon levels of South-East Italy. **J Environ Radioactiv**, v. 112, p. 160-164, 2012.

[9] IAEA - International Atomic Energy Agency. **Design and Conduct of Indoor Radon Surveys. Safety Report Series – No. 98**, Vienna: IAEA: Vienna, 2019. 128p.

[10] FLEMING, S.; THOMPSON, M.; STEVENS, R.; HENEGHAN, C.; PLÜDDEMANN, A.; MACONOCHIE, I.; TARASSENKO, L.; MANT, D. Normal ranges of heart rate and respiratory rate in children from birth to 18 years of age: a systematic review of observational studies. **Lancet**, v. 377 (9770), p. 1011-1018, 2011.

[11] DIAS, D. C. S. **Validation of the technique of Solid State Nuclear Track Detector for radon-222 determination in the air and monitoring of Early Childhood Education Centers in Poços de Caldas, Brazil**. Master's degree Dissertation on Science and Environmental Engineering, Universidade Federal de Alfenas, Poços de Caldas-Brazil, 2017.

[12] SILVA, N.C.; BOSSEW, P.; FERREIRA FILHO, A.L.; CAMPOS, T.F.; PEREIRA, A.J.; YOSHIMURA, E.M.; VEIGA, L.H.; CAMPOS, M.P.; ROCHA, Z.; PASCHUK, S.A.; BONOTTO, D.M. Towards a Brazilian Radon Map: Consortium Radon Brazil. **Radiat Prot Dosim**, v. 160 (1-3), p. 226-230, 2014.

[13] **CNEN - Comissão Nacional de Energia Nuclear. Diretrizes Básicas de Proteção Radiológica. CNEN Norma NN 3.01**, Rio de Janeiro: CNEN, 2014. 22p.

[14] ICRP - International Commission on Radiological Protection. **Recommendations of the International Commission on Radiological Protection**. **ICRP 60**, Oxford: ICRP, 1990. 211p.

[15] CNEN - Comissão Nacional de Energia Nuclear. **Níveis de intervenção e de ação para exposição crônica. CNEN Posição Regulatória 3.01/007**, Rio de Janeiro: CNEN, 2005. 3p.

[16] ICRP - International Commission on Radiological Protection. **Protection against radon at home and at work. ICRP 65**, Oxford: ICRP, 1993. 54p.

[17] CNEN - Comissão Nacional de Energia Nuclear. **Coeficientes de dose para indivíduos ocupacionalmente expostos. CNEN Posição Regulatória 3.01/003**, Rio de Janeiro: CNEN, 2011. 36p.

[18] CNEN - Comissão Nacional de Energia Nuclear. **Coeficientes de dose para exposição do público. CNEN Posição Regulatória 3.01/011**, Rio de Janeiro: CNEN, 2011. 101p.

[19] CNEN - Comissão Nacional de Energia Nuclear. **Requisitos de segurança e proteção radiológica para instalações mínero-industriais. CNEN Norma NN 4.01**, Rio de Janeiro: CNEN, 2016. 12p.

[20] NEMAN, R. S. **Measurement of radon-222 and daughters in the air: monitoring at Poços de Caldas-Brazil and activity comparisons involving 2 other techniques**. Doctorate Thesis, Physics Institute Gleb Wataghin - Universidade Estadual de Campinas, Campinas-Brazil, 2000.

[21] VEIGA, L. H. S.; KOIFMAN, S.; MELO, V.P.; SACHET, I. Preliminary indoor radon risk assessment at the Poços de Caldas Plateau, MG-Brazil. **J Environ Radioactiv**, v. 70, p. 161-173, 2002.

[22] CHAPMAN, N.A.; MCKINLEY, I.G.; FRANCA, E.P.; SHEA, M.E.; SMELLIE, J.A.T. The Poços de Caldas Project: an introduction and summary of its implications for radioactive waste disposal. **J Geochem Explor**, v. 45 (1-3), p. 1-24, 1992.

[23] SES-MG - Minas Gerais State Health Secretariat. **Poços de Caldas Plateau Project - Research on cancer and natural radiation: Minas Gerais-Brasil: 2004 - 2009**. Belo Horizonte: SES-MG: 2009.

[24] IBGE - Brazilian National Institute of Geography and Statistics. **Population Estimation 2017**. Brasília, Brazil. 2017. Available at: <https://www.ibge.gov.br/estatisticas/sociais/populacao/9103-estimativas-de-populacao.html?=&t=downloads>. Last accessed:18 Jan 2018.

[25] UNDP BRASIL - United Nations Development Program. **Human Development Index Municipalities Ranking 2014**. Brazil. 2014. Available at: <http://www.br.undp.org/content/brazil/pt/home/idh0.html>. Last accessed: 26 Mar 2018.

[26] INEP - Brazilian National Institute of Educational Studies and Research. **Statistical Synopsis of Basic Level Education 2018**. Brasília, Brazil. 2019. Available at: <http://inep.gov.br/sinopses-estatisticas-da-educacao-basica>. Last accessed: 17 March 2019.

[27] PHE - Public Health England. **PHE Intercomparison of Passive Radon Detectors**. **2015 Results.** London: Wellington House, 2016. 25p.

[28] TASL - Track Analysis Systems LTD. **Radon and Neutron dosimetry system. A complete system for etching, scanning and analyzing TASTRACK plastic nuclear track detector**. Bristol: TASL, 2012. 102p.

[29] CURRIE, L. A. Limits for qualitative detection and quantitative determination. **Anal Chem**, v. 40 (3), p. 586-593, 1968.

[30] BSI - British Standards Institution. **Measurement of radioactivity the environment — Air: radon-222. Part 4: Integrated measurement method for determining average activity concentration using passive sampling and delayed analysis**. BS ISO 11665-1:2012, United Kingdom: BS ISO, 2012.

[31] ANTONIAZZI, B.N.; SILVA, N.C.; CUNHA, T.N.; OTERO, U.B. **Poços de Caldas Plateau Project. Cancer Research and Natural Radiation – Incidence and Risk Behavior**. Belo Horizonte: SES-MG, 2013.

[32] COLGAN, P.A.; MCGARRY, A.T. Radon monitoring and control of radon exposure. In: **12TH INTERNATIONAL CONGRESS OF THE INTERNATIONAL RADIATION PROTECTION ASSOCIATION: STRENGTHENING RADIATION PROTECTION WORLDWIDE - HIGHLIGHTS, GLOBAL PERSPECTIVE AND FUTURE TRENDS**, 2010, Buenos Aires. Annals… Buenos Aires: International Radiation Protection Association, 2010.

[33] CHEN, J.; TRACY, B. L.; ZIELINSKI, J. M.; MOIR, D. Determining the sample size required for a community radon survey. **Health Phys**, v. 94 (4), p. 362-365, 2008.

[34] LEE, C. M.; KWON, M. H.; KANG, D. R.; PARK, T. H.; PARK, S. H.; KWAK, J. E. Distributions of radon concentrations in child-care facilities in South Korea. **J Environ Radioactiv**, v. 167, p. 80-85, 2016.

[35] AL-AZMI, D.; OKEYODE, I. C.; ALATISE, O. O.; MUSTAPHA, A. O. Setup and procedure for routine measurements of radon exhalation rates of building materials. **Radiat Meas**, v. 112, p. 6-10, 2018.

[36] PEREIRA, A.; LAMAS, R.; MIRANDA, M.; DOMINGOS, F.; NEVES, L.; FERREIRA, N.; COSTA, L. Estimation of the radon production rate in granite rocks and evaluation of the

implications for geogenic radon potential maps: A case study in Central Portugal. **J Environ Radioactiv**, v. 166, p. 270-277, 2017.

[37] ANDRADE, E.; MIRÓ, C.; REIS, M.; SANTOS, M.; MADRUGA, M. J. Assessment of radium activity concentration and radon exhalation rates in Iberian Peninsula building materials. **Radiat Prot Dosim**, v. 177 (1-2), p. 31-35, 2017.