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# Parallel Descriptive Assessments of Indoor Radon (2023) and Regional Hospital Cancer Registry Records (2003–2023) in Midwestern Santa Catarina, Brazil

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## Abstract

Radon is an established environmental cause of lung cancer, but residential surveillance is limited in Brazil. This study comprised two complementary, analytically independent components: indoor radon monitoring in Caçador, and Hospital Cancer Registry records of tracheal, bronchial and lung cancers in a 27-municipality regional analytical area, with comparisons to Santa Catarina and Brazil. Radosys RSKS CR-39 detectors were deployed for three months at 32 locations (26 residential, 6 commercial; 57 measurements); structured interviews assessed building and occupancy features. Registry records (2003–2023) were analysed descriptively. Median location-level radon concentration was 20.3 Bq/m$^3$ (range 7–112 Bq/m$^3$). One bedroom measurement and one commercial location exceeded the World Health Organization residential benchmark of 100 Bq/m$^3$, while all remained below the Brazilian 300 Bq/m$^3$ reference level for dwellings and other high-occupancy areas. Masonry with external coating (68.8%), ground-contact foundations (90.6%), and at least one active smoker in 34.4% of locations were reported. The regional analytical area comprised 356 records; across all territorial levels, men, adults aged 60–69 years, and adenocarcinoma predominated, with substantial missing data on smoking history, family history, and staging. Findings provide a regional baseline for targeted radon monitoring and improved cancer registry data quality.

**Keywords:** indoor radon; radon measurement; CR-39 detectors; dwellings; exposure assessment; indoor air quality; lung cancer; hospital cancer registry; Brazil

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## 1. Introduction

Lung cancer remains among the most prevalent and lethal malignancies worldwide, and its burden has continued to grow in many low- and middle-income countries, including Brazil, despite advances in prevention and treatment [1,2]. Tobacco smoking still accounts for the large majority of cases [1,2], while environmental exposures, including radon, are established contributors to lung cancer risk and are particularly relevant among never-smokers [3,4]. Understanding how these exposures intersect with living conditions, healthcare access, and the quality of health information systems is central to public health, since prevention strategies that ignore territorial and environmental context tend to miss the populations who need them most.

Among environmental carcinogens, radon holds a distinctive place. It is the only naturally occurring radioactive gas classified as a Group 1 human carcinogen by the International Agency for Research on Cancer, and it is the principal established environmental cause of lung cancer [3,4]. In the United States alone, radon is considered the second leading cause of lung cancer overall and the leading cause among never-smokers [5]. It arises naturally from the decay of uranium in soil and rock and can accumulate indoors, particularly in poorly ventilated dwellings at ground-floor level. Pooled analyses of residential studies have confirmed a dose–response relationship between radon exposure and lung cancer risk, with substantially greater absolute lung cancer risk among smokers because of the combined effects of radon and tobacco [6]. Residential radon concentrations vary considerably between and within countries in Central and South America [7], and associations between residential radon and lung cancer have also been reported among never-smokers [8] and in a large prospective cohort [9]. Crucially, the level of exposure depends on geological substrate, construction practices, and occupant behaviour, which means exposure has to be assessed locally rather than assumed from national or international averages. Both radon and tobacco are, in principle, preventable exposures: tobacco through public health policy, radon through relatively simple housing-level interventions such as improved ventilation, sub-slab depressurisation, and sealing of entry points.

Important gaps nonetheless persist in low-to-moderate geogenic settings, where indoor radon concentrations tend to be lower on average but where population-level risk may still be underestimated because surveillance is limited or absent. Evidence from Latin America points to considerable heterogeneity in indoor radon distribution and to limited spatial coverage of existing measurements [7]. In Brazil, residential radon surveys have concentrated mainly in areas of higher geogenic potential, leaving low-uranium contexts, including large parts of the southern region, without any characterisation of residential exposure [7,10]. This gap is compounded by structural limitations in the completeness of hospital-based cancer registries, which remain the principal source of cancer information available in many Brazilian regions in the absence of population-based registries. Because these registries are service-based rather than population-based, the cases they capture reflect care-seeking and reporting patterns as much as underlying disease occurrence, and known gaps in variables such as smoking history and disease stage constrain their use for aetiological interpretation [11,12]. Describing local environmental measurements and regional registry data side by side, while remaining explicit about their descriptive and unlinked nature, may nevertheless help identify where surveillance needs to be strengthened.

From a regional surveillance perspective, environmental exposure monitoring and high-quality disease registration represent distinct but complementary prerequisites for future aetiological research. Their parallel description can identify where environmental measurements and health-information systems require strengthening before exposure–outcome relationships can be investigated appropriately. Accordingly, the two components of the present study were not integrated analytically. Rather, they were used to establish

separate environmental and health-information baselines within the same broader regional context in Midwestern Santa Catarina. Caçador, where indoor radon monitoring was conducted, is one of the municipalities included in the 27-municipality regional analytical area used for the Hospital Cancer Registry component. However, the indoor measurements from Caçador are not considered representative of radon exposure across the entire analytical area.

Caçador, in Midwestern Santa Catarina, southern Brazil, lies within the volcanic domain of the Serra Geral Formation [13], a geological context that, to our knowledge, has not previously been characterised for residential radon exposure. This study aimed to describe indoor radon concentrations in sampled residential and commercial locations in the municipality of Caçador, and to characterise Hospital Cancer Registry records of tracheal, bronchial and lung cancers within the 27-municipality regional analytical area over a 21-year period (from 2003 to 2023 inclusive), comparing these records with state and national patterns. These two analytically independent components are presented in parallel to identify environmental-monitoring and health-information priorities for regional surveillance; no individual-, address-, or time-level linkage between the datasets was performed, and no exposure–outcome association was estimated.

## 2. Materials and Methods

### *2.1. Study Design and Setting*

This observational study comprised two complementary descriptive components: a cross-sectional environmental survey of indoor radon concentrations and a descriptive analysis of Hospital Cancer Registry records. The two components were designed to provide complementary information for regional environmental health surveillance rather than to establish an individual-level association between radon exposure and cancer, which the study design does not permit.

The study was conducted in Midwestern Santa Catarina, southern Brazil, a region characterised by volcanic rocks of the Serra Geral Formation [13]. Indoor radon measurements were performed in residential dwellings and commercial premises in the municipality of Caçador as part of a multicentre Brazilian Radon Risk Project, coordinated through a collaboration between Brazilian and European research institutions.

### *2.2. Environmental Component*

#### 2.2.1. Selection of Indoor Locations

Given the predominance of Serra Geral volcanic rocks in the study region [13], and the absence of soil gamma-spectrometry maps for this area as for other parts of the country, the technical selection criteria were limited to ensuring geographical coverage across urban neighbourhoods and rural districts. The research team contacted the municipal Health Department, which authorised community health agents to accompany household visits and detector installation. Within each neighbourhood or rural district, households were identified based on the recommendation of the local health agent, prioritising residents who understood the purpose of the study and who could ensure that detectors remained undisturbed throughout the exposure period. All households invited to participate accepted; no refusals were recorded. Installations in six commercial establishments and offices were also accepted at the owners' request. Measurements from these premises were included as secondary indoor-environment observations and analysed separately from the residential dataset. No a priori statistical power or sample-size calculation was performed because the environmental component was designed as an exploratory descriptive monitoring campaign rather than a population-representative hypothesis-testing survey. No fixed quota was established for individual neighbourhoods or rural districts. The final analytical

sample covered 14 neighbourhoods/rural districts, with 1–6 monitored locations per area (Supplementary Table S2). Selection therefore aimed to obtain geographical coverage rather than a formally balanced spatial sample.

A total of 80 detectors were initially deployed across 43 indoor locations (37 residences and 6 commercial premises) between 17 and 27 January 2023 (installation, austral summer) and retrieved between 16 and 26 April 2023 (retrieval, austral autumn), yielding a three-month integrated exposure period. Following retrieval and data validation, 11 location records were excluded from the analytical dataset owing to detector loss, non-retrieval, or identification of a duplicated database record, yielding valid data from 32 locations (26 residential and 6 commercial) comprising 57 individual measurements. Sampling was purposive and non-probabilistic, guided by geographical coverage and by logistical constraints inherent to long-term passive detector deployment. This approach limits the generalisability of exposure estimates to the broader regional population and should be considered when interpreting spatial patterns.

#### 2.2.2. Radon Measurement and Quality Assurance

Indoor radon concentrations were measured using CR-39 solid-state nuclear track detectors (Radosys RSKS passive radon dosimeter; Radosys Kft., Budapest, Hungary; Supplementary Figure S1), deployed in accordance with World Health Organization (WHO) protocols [4]. The protocol aimed to deploy two detectors per residential location, one in the main living area and one in an occupied bedroom, where feasible, positioned away from windows, heat sources, and sealed surfaces, at a height of 1.0–1.5 m above floor level.

After retrieval, detectors were analysed at the coordinating laboratory. Radon concentration ($Bq/m^3$) was derived from nuclear track density following background correction and application of the calibration factor used by the analysing laboratory for the RSKS detector system, in accordance with the manufacturer's dosimetry procedures [14]. Detectors were systematically subjected to background control, which consistently showed negligible background levels, accounting for less than 1% of the total track count. The analytical procedure was associated with an estimated relative measurement uncertainty of approximately 9%. Accordingly, individual concentration values should not be interpreted as uncertainty-free exact measurements. CR-39 detectors do not have a single universally defined detection limit, as this physical, solid-state technology quantifies exposure through track density rather than an electronic signal threshold. The measurable range depends on background track density, exposure duration, and the counting methodology used. A detection limit of approximately 6 $Bq/m^3$ has been reported for 90-day exposures using the same Radosys RSKS detector type [15]. A site-specific detection limit was not experimentally determined for the present measurement protocol. At high radon concentrations, increasing track density can conversely lead to track overlap and counting saturation, which may cause underestimation; however, this was not considered a concern for the concentration range observed in this study [16].

For locations with valid measurements in both indoor positions, the location's radon concentration was calculated as the mean of the living-area and bedroom measurements. This location-level value was used solely as a descriptive building-level summary and as the point value for spatial representation, and it was not intended to represent an occupancy-weighted estimate of personal radon exposure. Room-specific time–activity data were not collected; the arithmetic mean was used as a building-level descriptor and was not intended to reflect time spent in each room. Accordingly, living-area and bedroom measurements were also retained and reported separately. Where only one valid detector measurement was available, that single measurement was retained as representative of the

location's indoor radon concentration for the descriptive and spatial analyses. Additional methodological details are provided in the Supplementary Methods.

#### 2.2.3. Built-Environment and Participant/Occupancy Variables

During detector installation, trained researchers conducted structured interviews to obtain demographic and behavioural information (age, smoking status, occupation, and length of residence) and dwelling characteristics (construction materials, ventilation features, and occupancy patterns), using standardised questionnaires previously applied in Brazilian radon surveys.

#### 2.2.4. Environmental Data Analysis

Indoor radon concentrations are described using median, interquartile range, range, and mean ± standard deviation, separately for residential and commercial locations. The primary unit of analysis was the residential location ($n$ = 26), and commercial premises ($n$ = 6) were analysed and reported separately as a secondary, descriptive dataset. The spatial distribution of residential radon concentrations is presented as a point map of location-level values; the commercial location with the highest measured concentration (Section 3.4) is additionally highlighted on the map for context, although the primary spatial analysis is restricted to residential locations. No geostatistical interpolation was performed, given the purposive, non-probabilistic sampling design and the absence of a validated spatial model for this dataset. Point locations are presented at a map scale (1:100,000) and coordinate precision that preclude reliable identification of individual dwellings, and no street-level addresses or high-precision coordinates are disclosed in the published figure or Supplementary Material. Norma ANSN 3.01 of the National Nuclear Safety Authority establishes a reference level of 300 Bq/m$^3$ for radon in dwellings and other areas with high occupancy factors, including workplaces [17]. In workplaces where concentrations cannot be reduced below 1000 Bq/m$^3$, the requirements for occupational exposure in planned exposure situations apply [17]. Because measurements covered a single three-month period and no validated seasonal correction factor was available for Caçador, measured concentrations were not extrapolated to annual effective dose. Individual room-specific time–activity data were also unavailable. For the same reason, excess lifetime cancer risk was not estimated, as doing so would require multiple model-based assumptions not supported by the present exploratory monitoring design [4].

### *2.3. Hospital Registry Component*

#### 2.3.1. Data Source and Study Population

Lung and tracheal cancer cases (ICD-10 C33–C34) diagnosed between 2003 and 2023 were obtained from the Brazilian Hospital Cancer Registry (Registro Hospitalar de Câncer, RHC) database, maintained by the Brazilian National Cancer Institute (Instituto Nacional de Câncer, INCA) through the Integrador RHC platform, with data extracted on 24 August 2026. Only cases classified as analytical by the RHC/INCA were included. According to Integrador RHC technical criteria, analytical cases are malignant neoplasms for which treatment planning and treatment were performed at the reporting hospital, together with follow-up of disease progression [18]. This restriction was adopted to reduce the potential for duplicate counting associated with subsequent care at different institutions. No further individual-level deduplication across hospitals was performed. Patients with multiple primary tumours may contribute more than one record where these represent distinct primary tumours under RHC/INCA registration rules.

Tracheal cancer (C33) was analysed together with bronchial and lung cancer (C34), given their shared principal risk factor profile, notably tobacco exposure. Tracheal cases represented less than 0.25% of the analytical sample. Due to reporting delays affecting recent

years, records for 2022–2023 remain in the descriptive dataset but should be interpreted with caution.

Analyses were conducted at three territorial levels: Brazil, the state of Santa Catarina, and a 27-municipality regional analytical area defined according to the CISAMARP (Consórcio Público Interfederativo de Saúde do Alto Vale do Rio do Peixe) composition considered when the study area was established [19]. Under the current healthcare regionalisation of Santa Catarina, these municipalities are distributed across the Alto Vale do Rio do Peixe and Meio Oeste Health Regions, both within the Meio Oeste Health Macroregion [20]. Accordingly, this analytical area should not be interpreted as a single official Health Region (Supplementary Table S1). Records were assigned to territorial levels according to the patient's municipality of origin (residence) recorded in the RHC "Procedência" field [18].

#### 2.3.2. Variables and Classifications

Variables included year of diagnosis, sex, age group, education, smoking history, family history of cancer, histological subtype, and stage as recorded in the RHC/INCA [18]. Histological classification followed the WHO Classification of Thoracic Tumours (2021) based on ICD-O-3 codes recorded in the registry [21,22]. For descriptive analysis, stage was grouped a priori as Stage 0, early (I–II), advanced (III–IV), and missing/non-classifiable. Registry-coded categories were retained as recorded, and no imputation was performed.

#### 2.3.3. Registry Data Analysis

Annual Hospital Cancer Registry records were summarised as relative frequencies of the total 2003–2023 analytical caseload within each territorial level to characterise the temporal distribution of registry activity. Because the Hospital Cancer Registry is service-based and does not provide population denominators, these proportions were not interpreted as measures of population incidence or disease risk. Regional distributions of sociodemographic, behavioural and clinical variables were summarised using proportions, with registry-coded categories retained as recorded and missing data reported separately. To contextualise potential reporting delays in the most recent RHC years, counts for 2022 and 2023 were descriptively compared with corresponding counts from the INCA Oncology Panel, accessed on 24 August 2026 [23]. Because the two sources differ in data inputs, coverage, and purpose, the resulting ratios were treated only as descriptive cross-source comparisons and not as formal estimates of RHC completeness.

### *2.4. Statistical Analysis*

Descriptive statistics (median, interquartile range, range, and mean ± standard deviation) were used to summarise indoor radon concentrations. An exploratory comparison of location-level radon concentrations between residential and commercial premises was performed using the Mann–Whitney U test. Because four of the six commercial locations contributed a single detector measurement, whereas most residential values were two-room means, this comparison should be interpreted with additional caution. Given the purposive sampling design and the small number of commercial premises, this analysis was interpreted descriptively rather than as population-level inference. Categorical variables from the Hospital Cancer Registry were summarised as absolute and relative frequencies, with missing data retained as separate categories. Annual relative frequencies of registry records were calculated as the number of analytical cases recorded in each calendar year divided by the total 2003–2023 analytical caseload within the corresponding territorial series, multiplied by 100. Temporal trends in these annual relative frequencies were assessed using simple linear regression restricted to 2003–2021 because records for 2022–2023 were considered provisional owing to reporting delays. Calendar year was entered as the independent variable and annual relative frequency as the dependent variable. The regression slope

(β), expressed as percentage points per year, and the coefficient of determination ($R^2$) were reported as descriptive indicators of registry activity rather than population incidence. All analyses were performed using Stata version 12.0 (StataCorp, College Station, TX, USA).

### *2.5. Ethical Considerations*

The study was approved by the institutional Research Ethics Committee (approval number 5.781.863). All procedures were conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from participants in the environmental component, and the requirement for individual consent was waived for the analysis of anonymised secondary registry data.

## 3. Results

### *3.1. Selection and Characteristics of Monitored Locations*

A total of 80 detectors were initially deployed across 43 indoor locations in the municipality of Caçador between January and April 2023. Following retrieval and data validation, 11 location records were excluded, yielding valid data from 32 locations (26 residential dwellings and 6 commercial premises) comprising 57 individual measurements (Table 1; Supplementary Table S2). Sampling locations were distributed across the urban perimeter and surrounding rural districts of Caçador (Figure 1).

**Table 1.** Indoor radon concentrations by location type and room type, Caçador, Santa Catarina, Brazil (January–April 2023).

| Location-Level Indoor Radon | Overall | Residential | Commercial |
|---|---|---|---|
| Valid locations, *n* | 32 | 26 | 6 |
| Median (IQR), Bq/m$^3$ | 20.3 (16.5–34.9) | 20.0 (16.5–33.6) | 26.5 (19.8–43.0) |
| Mean ± SD, Bq/m$^3$ | 29.4 ± 21.7 | 26.7 ± 16.7 | 41.3 ± 36.4 |
| Min–max, Bq/m$^3$ | 7.0–112.0 | 7.0–78.5 | 16.5–112.0 |
| Locations > 100 Bq/m$^3$, *n* (%) | 1 (3.1) | 0 (0.0) | 1 (16.7) |
| Individual Room Measurements | Living Areas | Bedrooms | |
| Valid measurements, *n* | 24 | 25 | |
| Median (IQR), Bq/m$^3$ | 20.0 (16.8–26.0) | 19.0 (17.0–36.0) | |
| Mean ± SD, Bq/m$^3$ | 24.4 ± 12.0 | 29.5 ± 24.1 | |
| Min–max, Bq/m$^3$ | 15.0–65.0 | 7.0–120.0 | |
| Measurements > 100 Bq/m$^3$, *n* (%) | 0 (0.0) | 1 (4.0) | |

IQR calculated by linear interpolation of the 25th and 75th percentiles. Location-level values represent the mean of living-area and bedroom measurements where both were valid; where only one valid measurement was available, that value was used; decimal values result from averaging whole-number room-level measurements (Supplementary Table S2). Room-type summaries include all valid residential room measurements (24 living-area and 25 bedroom measurements); 23 locations contributed paired measurements and three contributed a single valid measurement. WHO residential reference level, used here as a descriptive benchmark = 100 Bq/m$^3$; Brazilian reference level for dwellings and other high-occupancy areas, including workplaces = 300 Bq/m$^3$. No location exceeded the applicable Brazilian reference level. One commercial location (112 Bq/m$^3$) also serves as the owners' living quarters; the detector was installed in the commercial area only, and the location is classified as commercial on this basis. Individual detector measurements are subject to an estimated relative measurement uncertainty of approximately 9% (Section 2.2.2).

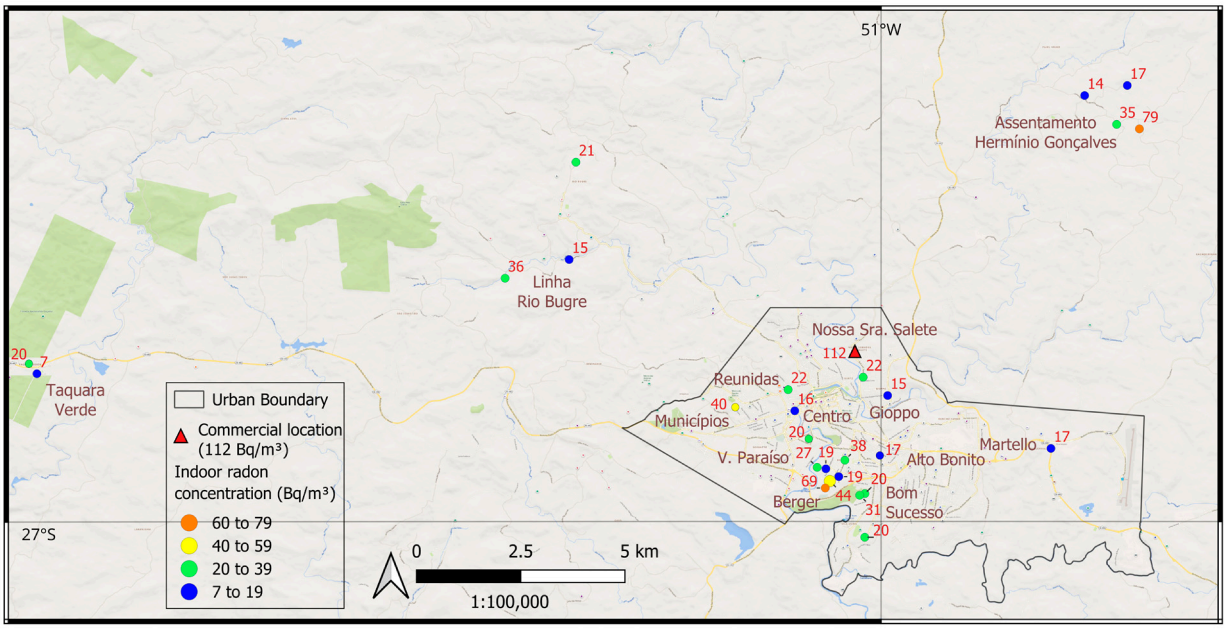



**Figure 1.** Location-level indoor radon concentrations (Bq/m$^3$) at 26 residential locations in Caçador, Santa Catarina, Brazil (January–April 2023). Neighbourhood and district names are shown in their official Portuguese form. Circles represent residential location-level values; numeric labels are rounded to the nearest Bq/m$^3$. One commercial location (112 Bq/m$^3$) is highlighted (red triangle) for context. The WHO residential reference level of 100 Bq/m$^3$ is used as a descriptive benchmark [4]; the Brazilian reference level is 300 Bq/m$^3$ for dwellings and other high-occupancy areas, including workplaces [17].

### *3.2. Built-Environment and Occupancy Characteristics*

Among the 32 monitored locations, masonry construction with external coating was the most frequent construction type (68.8%), followed by timber/wood construction (18.8%), mixed masonry/timber construction (9.4%), and masonry without external coating (3.1%; Table 2). All locations had covered flooring, and the large majority (90.6%) were built directly on ground-contact foundations, with the remainder elevated or of another foundation type (9.4%). Regarding occupancy patterns, 56.3% of occupants had used the same location for more than 10 years, while the remainder (43.8%) had done so for a shorter period. Active smoking among occupants was reported at 34.4% of locations, with a mean smoking duration of 24 years and an average consumption of 12 cigarettes per day among active smokers (Table 2).

**Table 2.** Built-environment and occupancy characteristics of monitored locations, Caçador, Santa Catarina, Brazil ($n$ = 32).

| Characteristic | Overall |
|---|---|
| Construction material | |
| Masonry with external coating | 22 (68.8) |
| Timber/wood construction | 6 (18.8) |
| Mixed masonry/timber construction | 3 (9.4) |
| Masonry without external coating | 1 (3.1) |
| Flooring | |
| Covered flooring | 32 (100.0) |
| Foundation | |
| Ground-contact | 29 (90.6) |
| Elevated/other | 3 (9.4) |

**Table 2.** *Cont.*

| Characteristic | Overall |
|---|---|
| Duration of occupancy | |
| >10 years | 18 (56.3) |
| ≤10 years | 14 (43.8) |
| Smoking status among occupants | |
| Active smoker | 11 (34.4) |
| Mean smoking duration, years | 24 |
| Mean cigarettes/day | 12 |
| Non-active smoker | 21 (65.6) |

Foundation type and duration of occupancy were recorded as dichotomous variables in the original field data, with no further subcategories available; these are presented as *n* (%) accordingly. "Occupancy" refers to habitual use of the location, whether residential or commercial, given that behavioural and dwelling-characteristic data were collected uniformly across all 32 monitored locations.

### *3.3. Indoor Radon Concentrations in Residences*

At the location level ($n$ = 26), the median concentration was 20.0 Bq/m$^3$ (IQR 16.5–33.6; range 7.0–78.5 Bq/m$^3$). Across the 49 individual residential room measurements, one bedroom measurement reached 120 Bq/m$^3$ (estimated relative measurement uncertainty of approximately 9%, corresponding to ~11 Bq/m$^3$ at this concentration), exceeding the WHO residential reference level of 100 Bq/m$^3$, used here as a descriptive benchmark [4]. However, the corresponding residential location mean (37 and 120 Bq/m$^3$, living area and bedroom, respectively) was 78.5 Bq/m$^3$, and no residential location mean exceeded this benchmark. Both the individual measurement and the residential location mean remained well below the Brazilian reference level of 300 Bq/m$^3$ [17] (Table 1; Figure 1). Living-area and bedroom concentrations were descriptively similar in median values (median 20.0 vs. 19.0 Bq/m$^3$; Table 1), although bedrooms showed a wider range, reflecting the single elevated measurement noted above.

### *3.4. Secondary Description of Commercial Premises*

At the location level ($n$ = 6), the median commercial concentration was 26.5 Bq/m$^3$ (IQR 19.8–43.0). One commercial location recorded a single valid measurement of 112 Bq/m$^3$ (estimated relative measurement uncertainty of approximately 9%, corresponding to ~10 Bq/m$^3$ at this concentration). As only one valid measurement was available at this location, the location-level value corresponded to this single measurement rather than to a two-room mean. This value exceeded the WHO residential reference level, used here as a descriptive benchmark [4], but remained below the Brazilian reference level of 300 Bq/m$^3$ [17]. These premises also serve as the owners' living quarters, located at the rear of the property; the detector was installed in the commercial area, and the location is classified as commercial on this basis, as no detector was placed in the residential portion of the property. Commercial premises are reported descriptively and were not included in the primary residential analysis, given differences in occupancy patterns and ventilation conditions relative to dwellings.

Commercial premises had a numerically higher median location-level concentration than residential locations (26.5 versus 20.0 Bq/m$^3$), although no statistically significant difference was observed between the two groups (Mann–Whitney U = 54.5; $p$ = 0.256).

### *3.5. Characteristics of Hospital Cancer Registry Records (2003–2023)*

A total of 163,482 analytical cases of tracheal, bronchial and lung cancer (ICD-10 C33–C34) were recorded in Brazil, 9764 in Santa Catarina, and 356 in the regional analytical area between 2003 and 2023 (Table 3). Across all three territorial levels, records were more frequent among men (58.6% Brazil; 63.5% Santa Catarina; 61.8% regional analytical

area) and among individuals aged 60–69 years (35.8% Brazil; 36.9% Santa Catarina; 38.8% regional analytical area). A substantial proportion of cases had low educational attainment (no formal education or incomplete primary education: 41.5% Brazil; 47.3% Santa Catarina; 42.1% regional analytical area), although educational data were also missing in 25.9%, 18.1% and 32.0% of records, respectively.

**Table 3.** Sociodemographic, behavioural and clinical characteristics of Hospital Cancer Registry analytical cases (RHC/INCA), by territorial level, 2003–2023.

| Characteristics | Brazil, *n* (%) | Santa Catarina, *n* (%) | Regional Analytical Area, *n* (%) |
|---|---|---|---|
| Total Analytical Cases | 163,482 | 9764 | 356 |
| Sex | | | |
| Female | 67,728 (41.4) | 3561 (36.5) | 136 (38.2) |
| Male | 95,747 (58.6) | 6202 (63.5) | 220 (61.8) |
| Unknown | 7 (<0.1) | 1 (<0.1) | 0 (0.0) |
| Age (years) | | | |
| <40 | 3821 (2.3) | 207 (2.1) | 6 (1.7) |
| 40–49 | 11,895 (7.3) | 777 (8.0) | 29 (8.1) |
| 50–59 | 38,221 (23.4) | 2516 (25.8) | 101 (28.4) |
| 60–69 | 58,522 (35.8) | 3605 (36.9) | 138 (38.8) |
| 70–79 | 40,464 (24.8) | 2126 (21.8) | 70 (19.7) |
| ≥80 | 10,552 (6.5) | 532 (5.4) | 12 (3.4) |
| Missing | 7 (<0.1) | 1 (<0.1) | 0 (0.0) |
| Educational attainment | | | |
| None | 12,619 (7.7) | 500 (5.1) | 22 (6.2) |
| Incomplete primary | 55,173 (33.7) | 4123 (42.2) | 128 (36.0) |
| Complete primary | 25,507 (15.6) | 1596 (16.3) | 48 (13.5) |
| Secondary | 18,806 (11.5) | 1136 (11.6) | 29 (8.1) |
| Incomplete higher | 721 (0.4) | 90 (0.9) | 3 (0.8) |
| Complete higher | 8264 (5.1) | 547 (5.6) | 12 (3.4) |
| Missing | 42,392 (25.9) | 1772 (18.1) | 114 (32.0) |
| Smoking history | | | |
| Current smoker | 39,146 (23.9) | 3375 (34.6) | 115 (32.3) |
| Former smoker | 23,528 (14.4) | 1866 (19.1) | 95 (26.7) |
| Never smoker | 15,715 (9.6) | 1276 (13.1) | 39 (11.0) |
| Not applicable | 379 (0.2) | 153 (1.6) | 5 (1.4) |
| Not assessed | 1444 (0.9) | 7 (0.1) | 0 (0.0) |
| Missing | 83,270 (50.9) | 3087 (31.6) | 102 (28.7) |
| Family history of cancer | | | |
| Yes | 26,974 (16.5) | 2264 (23.2) | 105 (29.5) |
| No | 26,297 (16.1) | 1928 (19.7) | 84 (23.6) |
| Missing | 110,211 (67.4) | 5572 (57.1) | 167 (46.9) |
| Histological group | | | |
| Adenocarcinoma and variants | 61,804 (37.8) | 3587 (36.7) | 146 (41.0) |
| Squamous cell carcinoma | 38,418 (23.5) | 2023 (20.7) | 65 (18.3) |
| Small-cell carcinoma (SCLC) | 13,817 (8.5) | 803 (8.2) | 21 (5.9) |
| Other specified epithelial/NSCLC | 12,905 (7.9) | 818 (8.4) | 20 (5.6) |
| Neuroendocrine tumours (non-SCLC) | 5147 (3.1) | 163 (1.7) | 7 (2.0) |
| Other rare malignancies | 1775 (1.1) | 90 (0.9) | 4 (1.1) |
| NOS/unspecified | 28,046 (17.2) | 2202 (22.6) | 88 (24.7) |
| Other/unspecified malignant histologies | 1570 (1.0) | 78 (0.8) | 5 (1.4) |

**Table 3.** *Cont.*

| Characteristics | Brazil, *n* (%) | Santa Catarina, *n* (%) | Regional Analytical Area, *n* (%) |
|---|---|---|---|
| Stage at diagnosis | | | |
| Stage 0 | 274 (0.2) | 10 (0.1) | 0 (0.0) |
| Early (I–II) | 16,282 (10.0) | 519 (5.3) | 27 (7.6) |
| Advanced (III–IV) | 99,385 (60.8) | 4925 (50.4) | 206 (57.9) |
| Missing/non-classifiable | 47,541 (29.1) | 4310 (44.1) | 123 (34.6) |

Data source: Hospital Cancer Registry (RHC/INCA), analytical cases only, extracted 24 August 2026. Missing data were retained in the denominator and reported as a separate category; no imputation was performed. Histological classification followed the WHO Classification of Thoracic Tumours (2021) [21,22].

Missing information was substantial for several variables: family history of cancer was unrecorded in 67.4% of Brazilian records, 57.1% in Santa Catarina, and 46.9% in the regional analytical area; smoking history was unrecorded in 50.9%, 31.6%, and 28.7%, respectively. Among records with available smoking information, current or former smoking was frequent across all three territorial levels (Table 3).

### *3.6. Histological Group and Stage at Diagnosis*

Adenocarcinoma and its variants were the most frequently recorded histological group at all three territorial levels (37.8% Brazil; 36.7% Santa Catarina; 41.0% regional analytical area), followed by squamous cell carcinoma (23.5%, 20.7% and 18.3%, respectively; Table 3). Staging information was missing or non-classifiable in 29.1% of Brazilian records, 44.1% of Santa Catarina records, and 34.6% of regional analytical area records. Advanced-stage disease (III–IV) accounted for the largest proportion of all analytical cases at all territorial levels (60.8% Brazil; 50.4% Santa Catarina; 57.9% regional analytical area), while early-stage disease (I–II) accounted for a minority of records (10.0%, 5.3% and 7.6%, respectively).

### *3.7. Temporal Distribution of Registry Records*

Annual relative frequencies of analytical registry records showed a strong positive linear trend in Brazil during 2003–2021 ($\beta = 0.213$ percentage points/year, $R^2 = 0.933$) and a more moderate positive trend in Santa Catarina ($\beta = 0.198$ percentage points/year, $R^2 = 0.564$). In the regional analytical area, the estimated slope was also positive ($\beta = 0.224$ percentage points/year), but the linear fit was weak ($R^2 = 0.197$), reflecting marked year-to-year variability rather than a consistent temporal pattern (Figure 2). During the 2003–2021 trend-analysis period, annual relative frequencies in the regional analytical area ranged from 1.4% to 11.2%, compared with 1.7–6.9% across the Brazil and Santa Catarina series, consistent with the greater statistical instability expected when small annual case counts are expressed as percentages. Records for 2022 and, particularly, 2023 showed marked reductions relative to preceding years, consistent with reporting delays; these years were therefore shown for descriptive continuity only and excluded from trend estimation. These temporal patterns describe registry activity and should not be interpreted as changes in population incidence. Annual case counts and relative frequencies by territorial level are presented in Table 4.

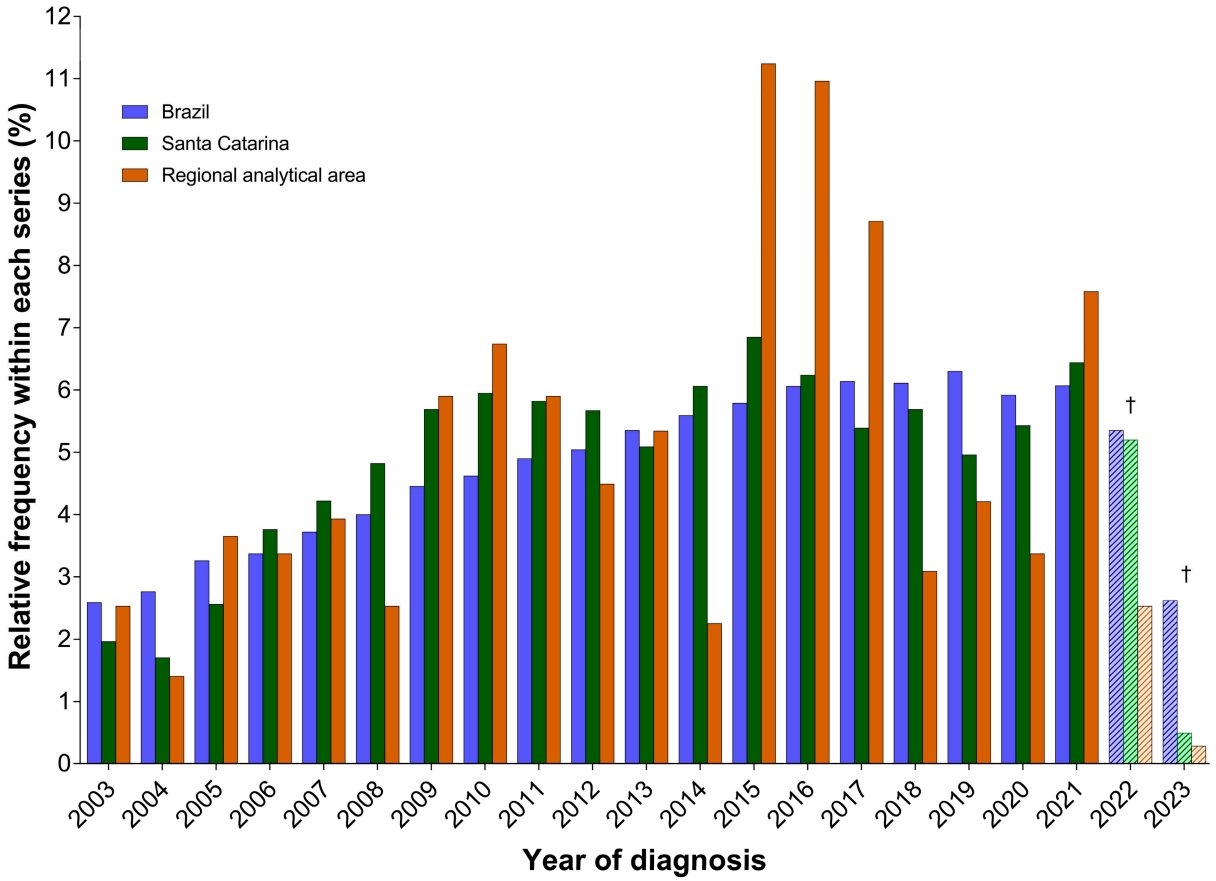



**Figure 2.** Annual relative frequency (%) of Hospital Cancer Registry analytical cases of tracheal, bronchial and lung cancer (ICD-10 C33–C34) in Brazil, Santa Catarina, and the regional analytical area, 2003–2023 (RHC/INCA; data extracted 24 August 2026; total analytical cases: Brazil, *n* = 163,482; Santa Catarina, *n* = 9764; regional analytical area, *n* = 356). Percentages were calculated using the total 2003–2023 analytical caseload within each territorial series as the denominator. † RHC/INCA records for 2022 and 2023 (hatched bars) are provisional and subject to reporting delays. To contextualise the marked reduction in recent RHC counts, these years were descriptively compared with corresponding counts from INCA Oncology Panel [23]. Because the RHC and INCA Oncology Panel differ in data sources, coverage, and purpose, these cross-source ratios were not interpreted as formal estimates of registry completeness. Data for 2022–2023 are shown for descriptive continuity only and were excluded from linear trend estimation, which was restricted to 2003–2021.

**Table 4.** Tracheal, bronchial and lung cancer (ICD-10 C33–C34) cases recorded by year and territorial level (Brazil, Santa Catarina and regional analytical area), 2003–2023.

| Year | Brazil, *n* (%) | Santa Catarina, *n* (%) | Regional Analytical Area, *n* (%) |
|---|---|---|---|
| 2003 | 4227 (2.59) | 191 (1.96) | 9 (2.53) |
| 2004 | 4509 (2.76) | 166 (1.70) | 5 (1.40) |
| 2005 | 5323 (3.26) | 250 (2.56) | 13 (3.65) |
| 2006 | 5508 (3.37) | 367 (3.76) | 12 (3.37) |
| 2007 | 6087 (3.72) | 412 (4.22) | 14 (3.93) |
| 2008 | 6538 (4.00) | 471 (4.82) | 9 (2.53) |
| 2009 | 7274 (4.45) | 556 (5.69) | 21 (5.90) |
| 2010 | 7554 (4.62) | 581 (5.95) | 24 (6.74) |
| 2011 | 8006 (4.90) | 568 (5.82) | 21 (5.90) |
| 2012 | 8245 (5.04) | 554 (5.67) | 16 (4.49) |
| 2013 | 8745 (5.35) | 497 (5.09) | 19 (5.34) |

**Table 4.** *Cont.*

| Year | Brazil, *n* (%) | Santa Catarina, *n* (%) | Regional Analytical Area, *n* (%) |
|---|---|---|---|
| 2014 | 9138 (5.59) | 592 (6.06) | 8 (2.25) |
| 2015 | 9466 (5.79) | 669 (6.85) | 40 (11.24) |
| 2016 | 9905 (6.06) | 609 (6.24) | 39 (10.96) |
| 2017 | 10,030 (6.14) | 526 (5.39) | 31 (8.71) |
| 2018 | 9996 (6.11) | 556 (5.69) | 11 (3.09) |
| 2019 | 10,294 (6.30) | 484 (4.96) | 15 (4.21) |
| 2020 | 9682 (5.92) | 530 (5.43) | 12 (3.37) |
| 2021 | 9924 (6.07) | 629 (6.44) | 27 (7.58) |
| 2022 † | 8747 (5.35) | 508 (5.20) | 9 (2.53) |
| 2023 † | 4284 (2.62) | 48 (0.49) | 1 (0.28) |
| Total | 163,482 (100) | 9764 (100) | 356 (100) |

Values are *n* (%) within each territorial level; percentages were calculated using the total 2003–2023 analytical caseload for each territorial series as the denominator. † RHC/INCA records for 2022–2023 are provisional and subject to reporting delays. To contextualise recent reporting, RHC counts were descriptively compared with corresponding counts from INCA Oncology Panel, accessed 24 August 2026 [23]. The RHC-to-INCA Oncology Panel count ratios were approximately 87% (Brazil) and 80% (Santa Catarina) for 2022, and 36% and 5%, respectively, for 2023. Because the RHC and INCA Oncology Panel differ in data sources, coverage, and purpose, these ratios are descriptive cross-source comparisons and should not be interpreted as formal estimates of registry completeness. Data for 2022–2023 were retained for descriptive continuity only and excluded from trend analyses; trend statistics were calculated using 2003–2021 data.

## 4. Discussion

This study characterised indoor radon concentrations in sampled residential and commercial locations in Caçador, and described lung cancer registry patterns in the 27-municipality regional analytical area over two decades, as two complementary descriptive components of regional environmental health surveillance rather than an integrated exposure–outcome analysis. The variability of indoor radon concentrations between monitored locations, although observed in a small purposive sample, supports the relevance of place-level environmental monitoring for targeted public health intervention. Nonetheless, this study did not test, and does not claim to demonstrate, any association between indoor radon concentrations and lung cancer in this population.

The low overall radon concentrations observed in Caçador are consistent with the generally lower radon potential of many mafic volcanic settings compared with uranium-enriched granitic and metamorphic terrains [24]. Despite generally low concentrations, some variability was observed across neighbourhoods and dwellings, plausibly related to differences in construction materials, ventilation, and ground contact, consistent with evidence from European studies demonstrating that indoor radon accumulation depends not only on geological substrate but also on construction materials, floor-soil contact, building age, and ventilation behaviour [25,26]. However, this study did not formally test associations between dwelling characteristics and radon concentration, and such comparisons would require a larger, probability-based sample. The maximum concentration recorded (120 Bq/m$^3$) exceeded the WHO reference level of 100 Bq/m$^3$ [4], used here as a descriptive benchmark, and was measured in a residential bedroom. The highest concentration among commercial premises (112 Bq/m$^3$) was identified in a poorly ventilated commercial property in the Nossa Senhora Salete neighbourhood that also serves as the owners' living quarters, though the residential portion of the property was not directly monitored. This value remained below the Brazilian reference level (300 Bq/m$^3$) [17]. Because this property combines commercial and residential use, it also illustrates a regulatory issue relevant to

mixed-use buildings. Norma ANSN 3.01 adopts the same reference level of 300 Bq/m$^3$ for dwellings and for other high-occupancy areas, including workplaces; the 1000 Bq/m$^3$ value serves only as the threshold above which occupational exposure requirements apply in workplaces where concentrations cannot be reduced [17]. The 300 Bq/m$^3$ reference level is therefore the relevant benchmark for both portions of this building. Because the detector was installed exclusively in the commercial area, follow-up monitoring should include the residential portion separately. Given the estimated relative measurement uncertainty of approximately 9%, the bedroom (120 Bq/m$^3$) and commercial (112 Bq/m$^3$) values lie close to the WHO benchmark, exceeding it by 20 and 12 Bq/m$^3$, respectively. Both values support targeted confirmatory monitoring and, if elevated concentrations persist, appropriate mitigation [4,17].

Lung cancer in never-smokers is increasingly recognised as a biologically and aetiologically distinct entity, in which residential radon is the principal established environmental determinant [27,28]. This concern is particularly relevant in Brazil, where radon exposure has been identified as a leading environmental cause of lung cancer in never-smokers, yet systematic residential surveillance remains limited [10]. Among records with known smoking status, never-smokers represented between 15.7% (regional analytical area) and 20.0% (Brazil) of cases. In the absence of individual-level exposure–outcome linkage, these registry-based figures cannot be attributed to radon exposure in this population. They are presented descriptively as a subgroup warranting continued attention. Nevertheless, because lung cancer risk increases with long-term residential radon exposure even at concentrations below commonly used reference levels [4,6], continued residential surveillance is warranted, particularly in dwellings with structural characteristics that may favour radon accumulation, such as limited ventilation and ground contact.

The temporal increase in lung cancer registry records across Brazil and Santa Catarina may reflect population ageing, cumulative tobacco exposure, changes in registration/reporting practices, and expanding diagnostic capacity [1,2]. The predominance of cases among men and individuals aged $\geq$60 years aligns with established international epidemiological patterns [1,2]. The regional analytical area showed no clear linear trend during 2003–2021 ($\beta$ = 0.224 percentage points/year, $R^2$ = 0.197), with pronounced year-to-year variability. Such variability is expected in small-area analyses, where low annual case counts amplify stochastic fluctuation [29]. The peak observed in 2015–2017 (40, 39 and 31 records, compared with a mean of approximately 18 records per year in 2003–2021) may reflect a combination of stochastic fluctuation and changes in the number of reporting hospitals or referral patterns. The relative contributions of these factors cannot be determined from the available data. These fluctuations should not be interpreted as evidence of a distinct temporal trajectory in this region.

The predominance of adenocarcinoma across all territorial levels warrants careful interpretation. Although adenocarcinoma is frequently associated with never-smokers and environmental carcinogens, including radon, its predominance alone does not establish an environmental aetiology, particularly given that current or former smoking was recorded in 59.0% of the regional analytical area cases overall (and in 84.3% of those with known smoking status, figures that reflect hospital-registry frequencies rather than population-level smoking prevalence). This distribution is consistent with the well-documented global shift towards adenocarcinoma following changes in cigarette design and deep-inhalation patterns [30].

A higher proportion of records with a documented family history of cancer was observed in the regional analytical area than at state and national levels. However, missingness for this variable was substantial across all territorial levels (46.9% in the regional analytical area, 57.1% in Santa Catarina, and 67.4% in Brazil), precluding meaningful in-

ferential comparison. Importantly, the registry variable captures family history of cancer in general rather than family history of lung cancer and therefore cannot be interpreted as evidence of familial susceptibility to lung cancer or directly compared with studies specifically examining first-degree family history of lung cancer [31]. Accordingly, this finding should be regarded as descriptive and hypothesis-generating only.

The predominance of advanced-stage disease across all territorial levels is consistent with challenges in timely access to lung cancer diagnosis and treatment previously documented in Brazil [12], although the registry data do not permit attribution of this pattern to specific diagnostic or healthcare pathways. Staging completeness also varied substantially across territorial levels, with missing/non-classifiable staging in 29.1% of Brazilian, 44.1% of Santa Catarina, and 34.6% of regional analytical area records. Limitations in the completeness of epidemiological and clinical variables have similarly been documented in Brazilian Hospital Cancer Registries [11], and should be considered when interpreting cross-territorial differences. At the local level, improving registry completeness should include strengthening structured collection of smoking history and stage at diagnosis during patient intake and registry abstraction. Where technically and clinically feasible, electronic validation rules or required completion fields could reduce avoidable missingness while retaining explicit "unknown/not assessed" categories when the information is genuinely unavailable. A large proportion of records indicated low educational attainment, particularly in Santa Catarina. Given the service-based nature of Hospital Cancer Registry data and the substantial proportion of missing educational information, this finding should be interpreted descriptively rather than as evidence of a population-level socioeconomic gradient. Socioeconomic barriers may nevertheless influence access to timely lung cancer diagnosis and treatment in Brazil [12]. These considerations reinforce the importance of addressing barriers to timely diagnosis and treatment within territorially targeted lung cancer control strategies.

Several limitations of this study should be acknowledged. The purposive, non-probabilistic sampling of indoor locations limits the generalisability of radon exposure estimates to the broader regional population. In addition, households were identified with the assistance of community health agents, who prioritised residents likely to keep the detectors undisturbed, which may have favoured more engaged households. Measurements covered a single three-month period spanning austral summer and autumn and were not seasonally adjusted. Therefore, they should not be interpreted as annual-average residential radon concentrations. The data cannot support inference about an association between residential radon and lung cancer because the two components were not linked at individual, address or temporal level. High and territorially variable proportions of missing registry data, particularly for smoking history, family history and TNM staging, constrain the interpretation of clinical and behavioural patterns. Finally, comparisons across territorial levels may be influenced by systematic differences in registry completeness and healthcare access that are not fully captured in the available data. Despite these limitations, this study offers several contributions to the evidence base: it provides, to our knowledge, the first characterisation of indoor radon concentrations in a basaltic volcanic setting in southern Brazil, alongside a transparent description of registry data missingness and recent reporting limitations that may inform future data quality improvements in the region.

Future monitoring campaigns should include winter measurements and, ideally, year-round monitoring. Seasonal variation in indoor radon has been documented internationally and in Brazil, with colder periods potentially producing higher indoor concentrations because of changes in ventilation and building pressure dynamics [4,32]. Winter-focused measurements in southern Brazil would therefore be valuable for identifying potential maximum residential exposures that may not have been captured by

the present summer–autumn campaign. These findings support targeted confirmatory radon monitoring at locations with elevated measurements and broader residential surveillance in Caçador, while precluding population-level inference from the present purposive, non-probabilistic sample.

## 5. Conclusions

Indoor radon concentrations were generally low across the monitored locations in Caçador, within the basaltic volcanic setting of the Serra Geral Formation. One bedroom measurement and one commercial location exceeded the WHO residential reference level of 100 Bq/m$^3$, used here as a descriptive benchmark, although no residential location mean did so, and all measurements remained below the Brazilian reference level of 300 Bq/m$^3$ for dwellings and other high-occupancy areas. Given the small, purposive sample and the single summer–autumn monitoring period, a larger probability-based residential survey incorporating winter and, ideally, year-round measurements is warranted to characterise spatial and seasonal radon variability more reliably. Hospital Cancer Registry records for the regional analytical area showed substantial missing information, particularly for smoking history, family history and staging, which limits the interpretation of clinical and behavioural patterns and constrains comparisons across territorial levels. These findings also support more systematic collection of smoking history and stage at diagnosis.

Overall, the parallel and complementary components support targeted confirmatory radon monitoring at locations with individual measurements above the WHO residential benchmark and continued efforts to improve the completeness of regional cancer registration.

**Supplementary Materials:** The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/atmos17101019/s1. Supplementary Methods: Radon detector installation and household procedures [33]; Table S1: Municipalities included in the 27-municipality regional analytical area (Santa Catarina, Brazil); Table S2: Distribution of radon detectors and measured concentrations by monitored location and neighbourhood in Caçador, Santa Catarina, Brazil; Figure S1: CR-39 solid-state nuclear track detector (RSKS type, Radosys) used for indoor radon measurements in this study.

**Author Contributions:** G.R.: Methodology, investigation, data curation, formal analysis, writing—original draft. O.A.d.S.F.: Conceptualisation, methodology, investigation, data curation, writing—original draft. S.A.P.: Data curation, formal analysis. J.N.C.: Data curation, formal analysis. C.V.B.: Data curation, formal analysis, writing—original draft. R.C.O.: Data curation, formal analysis, writing—original draft. R.F.F.d.C.: Data curation, formal analysis, writing—original draft. N.G.O.: Data curation, writing—original draft, writing—review and editing. J.G.C.: Data curation, formal analysis, validation, writing—original draft, writing—review and editing. E.R.A.: Conceptualisation, methodology, investigation, data curation, formal analysis, writing—original draft, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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**Institutional Review Board Statement:** The study was approved by the Research Ethics Committee of the University of Alto Vale do Rio do Peixe—UNIARP (approval number 5.781.863). As the epidemiological component used anonymised secondary data from the Brazilian Hospital Cancer Registry (RHC/INCA), individual informed consent was waived by the ethics committee in accordance with national regulations.

**Informed Consent Statement:** For all participants in the environmental component, written informed consent was obtained prior to detector deployment.

**Data Availability Statement:** RHC data are publicly accessible through INCA; environmental study data are available from the corresponding author upon reasonable request, subject to ethical/privacy restrictions.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| ANSN | Autoridade Nacional de Segurança Nuclear (National Nuclear Safety Authority) |
| CISAMARP | Consórcio Público Interfederativo de Saúde do Alto Vale do Rio do Peixe (Public Interfederative Health Consortium of the Alto Vale do Rio do Peixe) |
| CR-39 | Columbia Resin 39 (solid-state nuclear track detector material) |
| ICD-10 | International Classification of Diseases, 10th Revision |
| ICD-O-3 | International Classification of Diseases for Oncology, 3rd Edition |
| IQR | Interquartile range |
| $R^2$ | Coefficient of determination |
| RHC/INCA | Registro Hospitalar de Câncer/Instituto Nacional de Câncer (Hospital Cancer Registry/Brazilian National Cancer Institute) |
| SD | Standard deviation |
| TNM | Tumour, Node, Metastasis (staging classification) |
| WHO | World Health Organization |
| β | Regression slope (percentage points/year) |

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