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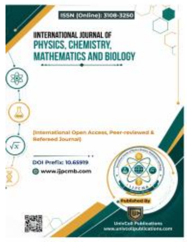

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Indoor Radon and Thoron Concentrations in Dwellings of Chandigarh, India: Seasonal Variability, Exhalation Characteristics and Radiological Dose Assessment

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Abstract

Radon (^222Rn) and thoron (^220Rn) are naturally occurring radioactive noble gases generated in the uranium-238 and thorium-232 decay series, respectively. Because they are chemically inert gases, they can migrate from soil and building materials into indoor environments, where their short-lived radioactive progeny may attach to aerosols and contribute to human inhalation exposure. Indoor exposure to radon is an important component of natural radiation exposure and has consequently received considerable attention in environmental radioactivity research. Thoron has a much shorter half-life than radon, but its progeny can nevertheless make a significant contribution to radiation dose under certain building and ventilation conditions. Chandigarh provides an important setting for studying these gases because of its distinctive urban development, variation in dwelling characteristics, soil conditions, construction materials and seasonal meteorology. The present paper reviews and synthesizes published measurements of indoor radon and thoron in dwellings of the Union Territory of Chandigarh and evaluates their radiological significance. Published investigations have reported indoor radon concentrations ranging from approximately 7.9 to 62.1 Bq m^-3 and thoron concentrations from approximately 0.15 to 99.2 Bq m^-3 across different measurement campaigns and dwelling groups. One Chandigarh investigation reported a mean radon concentration of 23.3 Bq m^-3 and a mean thoron concentration of 10.7 Bq m^-3, whereas another investigation using pin-hole based radon-thoron dosimeters reported mean concentrations of

39.9 Bq m^-3 for radon and 31.1 Bq m^-3 for thoron. Annual effective doses reported in these investigations were generally within the range associated with normal environmental exposure, although considerable dwelling-to-dwelling variability was observed. Soil and construction materials were identified as important sources of indoor radon, while ventilation, building characteristics and the spatial distribution of radioactive elements influenced indoor concentrations. The review demonstrates that Chandigarh generally exhibits relatively moderate indoor radon levels, but isolated dwellings can show substantially higher thoron concentrations. The findings emphasize the importance of measuring radon and thoron separately, because detectors that do not discriminate between the two gases may overestimate radon concentrations or obscure the contribution of thoron. Continued long-term monitoring, systematic seasonal measurements, characterization of building materials and development of a Chandigarh-specific indoor radon-thoron database are recommended.

Keywords: Radon; Thoron; ^222Rn; ^220Rn; Indoor air quality; Dwellings; Chandigarh; Radon progeny; Thoron progeny; Solid State Nuclear Track Detector; SSNTD; Exhalation rate; Annual effective dose; Natural radioactivity; Radiation exposure.

Introduction

Natural background radiation is an unavoidable component of the human environment. Among the naturally occurring radioactive materials contributing to human exposure, radon and its radioactive progeny occupy a particularly important position because radon can accumulate inside buildings and subsequently contribute to inhalation exposure. Radon is a radioactive noble gas produced predominantly through the decay of radium-226 in the uranium-238 decay series. Its principal isotope of environmental significance is ^222Rn, which has a half-life of approximately 3.82 days. Thoron, or ^220Rn, is produced from radium-224 in the thorium-232 decay series and has a much shorter half-life of approximately 55.6 seconds. Despite this difference, both gases can enter buildings and undergo radioactive decay, producing alpha-emitting progeny.

Radon and thoron differ substantially in their physical behaviour. The relatively long half-life of ^222Rn allows radon to migrate appreciable distances through soil pores and cracks in building foundations before entering indoor spaces. Thoron, by contrast, decays rapidly, so its indoor distribution is strongly influenced by the proximity of its source to the building interior. Consequently, building materials containing thorium-rich minerals and surfaces close to occupied spaces can be particularly relevant to indoor thoron concentrations.

The radiological importance of radon arises primarily from its decay products rather than from the chemically inert gas itself. Radon progeny such as polonium, lead and bismuth isotopes can attach to airborne particles. When inhaled, these alpha-emitting progeny may deposit in the respiratory tract. Long-term exposure to elevated concentrations is associated with an increased risk of lung cancer. Thoron also produces radioactive progeny, and its contribution to inhalation dose may become significant in particular indoor environments.

International assessments emphasize that indoor radon concentrations are controlled by a complex interaction of soil characteristics, geological conditions, building construction, ventilation, meteorological conditions and occupant behaviour. UNSCEAR has also emphasized that reliable assessment of radon exposure requires empirical measurements because prediction from building or geological characteristics alone is difficult.

India has considerable geological and environmental diversity, and measurements from different parts of the country demonstrate substantial spatial variation in indoor radon and thoron. A nationwide review based on measurements using Solid State Nuclear Track Detector (SSNTD)-based passive techniques reported ^222Rn concentrations across surveyed Indian locations ranging from 4.6 to 147.3 Bq m^-3, with an overall geometric mean of about 23 Bq m^-3.

Chandigarh is particularly suitable for indoor radon-thoron studies because it represents a planned urban environment where residential buildings of different construction characteristics occur within a relatively welldefined geographical area. Measurements undertaken in Chandigarh have demonstrated that both radon and thoron are detectable indoors and that their concentrations vary considerably among individual dwellings.

The objective of this paper is therefore to provide a comprehensive research-oriented synthesis of indoor radon and thoron measurements in Chandigarh, emphasizing concentration ranges, seasonal behaviour, dwelling characteristics, radon exhalation, progeny concentrations, radiation dose and implications for indoor environmental quality.

Scientific Background of Radon and Thoron

Origin of Radon

Radon is generated naturally through the radioactive decay of radium present in rocks and soils. The principal environmental isotope is ^222Rn, formed through the uranium-238 decay chain:

^238U → ^234Th → ^234Pa → ^234U → ^230Th → ^226Ra → ^222Rn

The transformation of radium-226 into radon-222 results in the formation of a radioactive noble gas. Since radon is chemically inert, it is not readily retained by soil minerals and can migrate through interconnected pores and fractures.

The amount of radon entering a building depends upon the radium content of the surrounding soil, radon generation and emanation, soil permeability, pressure differences between the building and ground, foundation characteristics and ventilation.

Origin of Thoron

Thoron is the common environmental name for ^220Rn, produced in the thorium-232 decay series:

^232Th → ^228Ra → ^228Ac → ^228Th → ^224Ra → ^220Rn

The half-life of ^220Rn is only about 55.6 seconds. Consequently, thoron generally cannot migrate as far from its source as radon. This short half-life produces strong spatial gradients near surfaces and makes thoron concentration particularly sensitive to the location of thorium-bearing materials.

Radon and Thoron Progeny

The health significance of radon and thoron is largely associated with their short-lived progeny. These radioactive decay products can attach to aerosols and enter the respiratory system. The alpha particles emitted during subsequent decay processes have high linear energy transfer and can deposit energy over short distances in biological tissue.

Consequently, indoor radiation assessment should consider not only the concentration of the parent gases but also progeny concentrations and equilibrium conditions.

Why Radon and Thoron Must Be Distinguished

A major methodological issue in indoor radiation studies is the distinction between radon and thoron. Some detectors respond to both gases, while radon-thoron discriminating dosimeters are designed to estimate them separately.

UNSCEAR has noted that thoron can represent an important component of exposure in certain dwellings and workplaces and that failure to distinguish thoron from radon can introduce errors in exposure assessment.

This distinction is particularly important in Chandigarh because published measurements have demonstrated that some dwellings can contain comparatively high thoron concentrations even when radon levels remain moderate.

Study Area: Chandigarh

Chandigarh is a planned urban centre in northern India and serves as the capital of both Punjab and Haryana while also functioning as a Union Territory. The city was developed according to a planned sector-based urban design. Residential areas include a variety of dwelling types, including independent houses, apartments and other constructed forms.

The urban environment is influenced by seasonal changes in temperature, humidity, atmospheric pressure and ventilation behaviour. During warmer months, windows and doors may remain open for longer periods, whereas colder conditions can encourage occupants to keep indoor spaces closed. Such changes can influence indoor radon and thoron concentrations.

The construction characteristics of Chandigarh dwellings are also important. Cement, sand, bricks, concrete and other mineral-based materials can contain naturally occurring uranium and thorium. The contribution of a building material to indoor radiation depends on its radionuclide concentration, porosity, emanation characteristics, surface area and ventilation conditions.

The Chandigarh studies available in the scientific literature demonstrate that the local indoor radon-thoron environment cannot be described adequately by a single concentration value. Instead, considerable dwelling-to-**dwelling variability occurs.**

Objectives of the Study

The principal objectives of the present research-oriented review are:

1. To examine published measurements of indoor ^222Rn and ^220Rn in Chandigarh dwellings.
2. To evaluate the range and average concentration of radon and thoron.
3. To examine variations among individual dwellings.
4. To assess the role of ventilation and building characteristics.
5. To examine radon exhalation from soil and construction-related materials.
6. To review radon and thoron progeny concentrations.
7. To evaluate annual effective radiation dose reported for Chandigarh dwellers.
8. To compare Chandigarh results with broader Indian and international observations.
9. To identify methodological issues associated with simultaneous radon-thoron measurement.
10. To recommend future monitoring strategies for Chandigarh.

Materials and Methods

Nature of the Present Study

The present paper is a synthesis of published measurements rather than a claim of newly collected field data. The principal Chandigarh datasets used for interpretation originate from published investigations of indoor radon and thoron in residential environments.

A major study by DR Praveen kumar investigated indoor radon, thoron and their progeny in Chandigarh dwellings and also examined the relationship between indoor concentrations and radon exhalation from nearby soil. The study reported seasonal variation and included measurements of gamma dose and annual effective dose.

A later investigation employed pin-hole based radon-thoron dosimeters with LR-115 track detectors for integrated measurements in Chandigarh dwellings. That study reported radon concentrations from 24.2 ± 1.1 to 62.1 ± 3.1 Bq m^-3 and thoron concentrations from 3.0 ± 0.1 to 99.2 ± 4.9 Bq m^-3.

Passive SSNTD Technique

Solid State Nuclear Track Detectors are widely used for integrated radon and thoron measurements. LR-115 and related track detectors register damage tracks produced by alpha particles emitted during radioactive decay.

In the Chandigarh investigations, detector-based dosimeters were positioned within selected dwellings for an extended exposure period. After exposure, the detectors were chemically etched so that latent alpha-particle tracks became visible and countable. The resulting track density was converted to radon or thoron concentration using experimentally established calibration factors.

The major advantage of passive SSNTDs is that they can provide time-integrated concentrations without requiring continuous electrical power. This makes them useful for long-duration indoor surveys.

Radon-Thoron Discrimination

A radon-thoron discriminating dosimeter employs detector geometry and diffusion characteristics that exploit the large difference between the half-lives of ^222Rn and ^220Rn.

The Chandigarh investigations used twin-cup or pin-hole based arrangements to distinguish radon and thoron contributions. This is important because a simple detector response may otherwise represent a combined alpha-track signal.

Measurement of Progeny

Radon and thoron progeny concentrations can be expressed in working levels (WL) or related equilibrium-equivalent quantities. The relationship between parent-gas concentration and progeny depends upon aerosol concentration, ventilation, attachment processes and radioactive equilibrium.

The Chandigarh measurements included progeny estimates, allowing the researchers to move beyond simple gas concentration and evaluate radiological exposure more comprehensively. One published dataset reported radon progeny concentrations from 0.8 to 4.2 mWL and thoron progeny concentrations from 0.01 to 0.6 mWL.

Radon Exhalation Measurements

Radon exhalation from soil is an important parameter because it provides an indication of the ability of the ground material to release radon into the surrounding environment.

The Chandigarh investigation measured both mass and surface exhalation rates from soil samples collected close to dwellings. The reported mass exhalation rate ranged from 0.9 to 1.9 mBq kg^-1 h^-1, with an average of 1.39 ± 0.29 mBq kg^-1 h^-1. The corresponding surface exhalation rate ranged from 20.7 to 42.3 mBq m^-2 h^-1, with an average of 31.4 ± 6.8 mBq m^-2 h^-1.

Results

Indoor Radon Concentration

Published Chandigarh measurements indicate substantial variability in indoor radon concentration.

In one investigation, indoor radon concentrations ranged from:

7.9 ± 0.5 to 39.2 ± 2.3 Bq m^-3

with an average of:

23.3 Bq m^-3.

A separate investigation using pin-hole based dosimeters reported a wider range:

24.2 ± 1.1 to 62.1 ± 3.1 Bq m^-3

with a reported average of approximately:

39.9 Bq m^-3.

These results demonstrate that the indoor radon environment in Chandigarh is variable and that the value obtained depends upon the dwelling sample, measurement period, detector methodology and environmental conditions.

Indoor Thoron Concentration

Thoron showed particularly strong dwelling-to-dwelling variability.

The earlier Chandigarh investigation reported thoron concentrations ranging from:

0.15 ± 0.01 to 24.6 ± 1.0 Bq m^-3

with an average of:

10.7 Bq m^-3.

The later pin-hole dosimeter investigation reported a considerably wider range:

3.0 ± 0.1 to 99.2 ± 4.9 Bq m^-3

with an average of approximately:

31.1 Bq m^-3.

The much wider thoron range is scientifically important. It indicates that some Chandigarh dwellings may experience relatively low thoron concentrations, while others may exhibit substantially elevated levels. This behaviour is consistent with the short half-life and strong source-location dependence of ^220Rn.

Summary of Published Chandigarh Results

Parameter	Published Chandigarh result
Radon concentration, earlier study	7.9–39.2 Bq m^-3
Mean radon, earlier study	23.3 Bq m^-3
Thoron concentration, earlier study	0.15–24.6 Bq m^-3
Mean thoron, earlier study	10.7 Bq m^-3
Radon concentration, later study	24.2–62.1 Bq m^-3
Mean radon, later study	39.9 Bq m^-3
Thoron concentration, later study	3.0–99.2 Bq m^-3
Mean thoron, later study	31.1 Bq m^-3
Earlier-study annual effective dose	0.3–1.4 mSv
Mean annual effective dose, earlier study	0.8 mSv
Soil mass exhalation rate	0.9–1.9 mBq kg^-1 h^-1
Mean soil mass exhalation rate	1.39 ± 0.29 mBq kg^-1 h^-1
Soil surface exhalation rate	20.7–42.3 mBq m^-2 h^-1
Mean surface exhalation rate	31.4 ± 6.8 mBq m^-2 h^-1

The values in the table are taken from published Chandigarh investigations and should not be interpreted as measurements collected specifically for the present paper.

Dwelling-to-Dwelling Variation

The Chandigarh measurements clearly demonstrate that indoor radon and thoron are not uniformly distributed among dwellings.

For example, one published dataset reported radon values of 15.8 Bq m^-3, 28.6 Bq m^-3, 7.9 Bq m^-3, 12.2 Bq m^-3 and 26.5 Bq m^-3 in five representative dwellings. The corresponding thoron values were 14.7, 7.4, 24.3, 0.1 and 3.5 Bq m^-3.

The contrast between the radon and thoron values is noteworthy. The dwelling with a radon concentration of only 7.9 Bq m^-3 showed a thoron concentration of approximately 24.3 Bq m^-3, whereas another dwelling with radon around 12.2 Bq m^-3 showed thoron close to the detection limit.

This indicates that radon and thoron should not be assumed to behave identically inside buildings.

Influence of Ventilation

Ventilation is one of the most important factors controlling indoor radon and thoron concentration.

A well-ventilated room permits radioactive gases to be diluted by outdoor air. Conversely, poorly ventilated spaces can permit gases to accumulate. The Chandigarh dataset included ventilation classifications and showed differences between dwellings having good, average and poor ventilation.

For example, a dwelling classified as having poor ventilation showed a radon concentration of 28.6 Bq m^-3, whereas a well-ventilated dwelling recorded a considerably lower radon value of 7.9 Bq m^-3. However, the relationship is not perfectly linear because soil properties, construction materials and source location also affect concentrations.

Thoron is even more complicated because of its short half-life. A source located close to an interior wall or floor can produce measurable thoron before the gas decays, whereas thoron originating farther away may decay before reaching the occupied room.

Therefore, ventilation should be considered together with source characteristics rather than as an independent controlling factor.

Seasonal Variation

Seasonal variation is an important characteristic of indoor radon studies.

The Chandigarh investigations included seasonal observations. Changes in atmospheric temperature, pressure, humidity, wind conditions and occupant ventilation behaviour can modify the movement and accumulation of radon indoors.

During periods when windows and doors remain closed, indoor ventilation decreases and radon may accumulate. During periods of greater natural ventilation, indoor concentrations may decline because of increased exchange with outdoor air.

The seasonal effect is not necessarily identical for every dwelling. Differences in floor level, foundation structure, building material, room usage and ventilation habits can produce different seasonal patterns.

Consequently, a single short-term measurement may not adequately represent annual exposure. Long-term integrated measurements are generally more useful for estimating annual average concentrations.

Soil Radon Exhalation

Soil is an important source of indoor radon. Radon produced in soil can migrate through pores and cracks and subsequently enter buildings.

The Chandigarh study found relatively low but measurable soil radon exhalation rates. The mass exhalation rate ranged from 0.9 to 1.9 mBq kg^-1 h^-1, while the surface exhalation rate ranged from 20.7 to 42.3 mBq m^-2 h^-1.

The average mass exhalation rate was reported as:

1.39 ± 0.29 mBq kg^-1 h^-1

and the average surface exhalation rate was:

31.4 ± 6.8 mBq m^-2 h^-1.

These values provide evidence that the soil surrounding Chandigarh dwellings can act as a source of radon, although the contribution to indoor concentration depends on the coupling between the ground and building interior.

A building with a relatively impermeable foundation may receive less soil-derived radon than a structure containing cracks, joints, openings or permeable construction materials.

Building Materials as Sources of Radon and Thoron

Building materials can also contribute to indoor radon and thoron. Materials derived from rocks and mineral aggregates may contain naturally occurring uranium, radium and thorium.

The contribution of building materials depends on:

- uranium and thorium concentration;
- radium distribution;
- porosity;
- radon emanation coefficient;
- material density;
- surface area;
- wall thickness;
- Indoor ventilation.

For thoron, source distance becomes particularly important. Because ^220Rn decays rapidly, thoron generated inside a wall or deep within a thick material may not reach the room in large quantities. Thoron generated near the surface of a material, however, can enter indoor air efficiently.

The Chandigarh literature specifically examined sand and soil samples associated with construction and residential environments. The later study also reported measurements of sand samples used for construction and found mass exhalation rates in the range of approximately 0.9–1.9 mBq kg^-1 h^-1.

Radon and Thoron Progeny

The concentration of radon and thoron gas alone does not fully describe inhalation risk. Their decay products are more directly relevant to alpha-particle deposition in the respiratory tract.

The earlier Chandigarh study reported radon progeny levels from approximately 0.8 to 4.2 mWL, with an average of approximately 2.5 mWL. Thoron progeny ranged from 0.01 to 0.6 mWL, with an average of approximately 0.3 mWL.

The equilibrium between radon and its progeny is influenced by ventilation and aerosol concentration. In a well-ventilated environment, progeny can be removed from indoor air more rapidly. Conversely, stagnant air can increase the residence time of airborne progeny.

For radiation-risk assessment, therefore, parent-gas measurements should ideally be complemented by progeny measurements or suitable equilibrium assumptions.

Annual Effective Dose

The annual effective dose represents an estimate of radiation exposure received by inhabitants as a result of inhalation of radon and thoron progeny.

The published Chandigarh study reported annual effective doses ranging from:

0.3 to 1.4 mSv

with an average of:

0.8 mSv.

These values indicate that, for the investigated dwellings, the estimated annual dose was within the range expected for environmental exposure and did not indicate an unusually high radiological burden across the sampled homes.

However, dose should not be evaluated solely from an average value. Individual dwellings may have concentrations substantially different from the population mean. Furthermore, the later Chandigarh investigation reported higher maximum radon and especially thoron concentrations than the earlier dataset, illustrating the importance of broader sampling.

Comparison with Indian Measurements

The Chandigarh results can be placed in the context of broader Indian measurements.

A nationwide review of indoor ^222Rn and ^220Rn measurements reported that indoor radon concentrations across surveyed Indian locations ranged from 4.6 to 147.3 Bq m^-3, with an overall geometric mean of approximately 23 Bq m^-3.

The mean radon concentration of 23.3 Bq m^-3 reported in one Chandigarh investigation is therefore close to the overall Indian geometric mean reported in that nationwide review.

The later Chandigarh mean of approximately 39.9 Bq m^-3 is higher, but remains within the broad range observed across Indian locations.

It is important, however, to avoid interpreting these comparisons as evidence that one city is intrinsically safer or more hazardous than another. Differences in detector type, sampling period, dwelling selection, seasonal conditions and measurement protocols can substantially affect results.

Comparison with International Reference Values

The interpretation of indoor radon concentration should be based on established radiological protection principles rather than a simple division between "safe" and "unsafe" concentrations.

The International Commission on Radiological Protection has developed reference-level concepts for radon exposure, while national authorities may adopt specific action or reference levels.

The earlier Chandigarh study stated that the measured indoor radon values were below the lower reference limits considered in its assessment and were comparable to the world average value used by the authors.

Nevertheless, the existence of relatively low average concentrations does not eliminate the importance of monitoring. Radon exposure is cumulative, and individual homes can differ considerably from an area-wide average.

Discussion

The available Chandigarh evidence indicates that indoor radon and thoron concentrations are measurable but generally moderate in the investigated residential environments. At the same time, the wide range observed in individual dwellings demonstrates that an area-wide average cannot adequately describe the exposure of every resident.

The mean radon concentration of 23.3 Bq m^-3 from one study is relatively low, while the later reported mean of 39.9 Bq m^-3 is higher. The difference could reflect several factors, including the selection of dwellings, measurement season, detector design and changes in building conditions.

The thoron results are especially significant. In the earlier study, the mean thoron concentration was 10.7 Bq m^-3, while the later study reported a mean of 31.1 Bq m^-3 and a maximum value approaching 100 Bq m^-3.

This large variation supports the conclusion that thoron deserves independent consideration in indoor radiation surveys.

Another important observation is that radon and thoron do not necessarily correlate strongly at the individual dwelling level. A house may have moderate radon but comparatively high thoron, or vice versa. This occurs because the sources and transport mechanisms of the two gases differ.

The short half-life of thoron means that building surfaces and materials can become particularly important sources. Radon, on the other hand, can migrate from soil and foundations over greater distances.

The Chandigarh results therefore reinforce the importance of radon-thoron discriminating measurement techniques.

Correlation with Radon Exhalation

The relationship between indoor radon concentration and radon exhalation from soil is another important aspect of the Chandigarh research.

Soil exhalation provides a measure of the rate at which radon is released from a material into the surrounding environment. A positive relationship between soil exhalation and indoor radon would be physically reasonable because greater radon release increases the potential source available for entry into buildings.

However, indoor concentration is not controlled by exhalation alone. A dwelling can have a relatively high source strength but low indoor concentration if ventilation is efficient. Conversely, a building with modest source strength can experience higher concentration if ventilation is poor.

Therefore, indoor radon concentration can be conceptually represented as a function of several interacting variables:

Indoor radon ≈ source strength × transport efficiency × building entry factor × accumulation factor where the accumulation factor is strongly affected by ventilation.

The Chandigarh studies provide evidence that soil exhalation is useful as a source indicator but should not be used as a substitute for direct indoor measurements.

Importance of Ventilation and Building Design

Modern urban buildings can have relatively low natural ventilation because of air-conditioning, sealed windows and energy-efficient construction. Although such designs can improve thermal comfort and energy efficiency, reduced air exchange may increase the residence time of naturally occurring indoor contaminants.

For radon-prone buildings, adequate ventilation can reduce indoor concentrations by increasing dilution. However, ventilation strategies should be designed carefully because excessive ventilation can increase energy consumption.

Passive architectural measures can include improved foundation sealing, reduction of cracks and openings between soil and living spaces, and provision for controlled air exchange.

In existing dwellings, the first step should be measurement. It is not scientifically appropriate to assume that every building in an area has elevated radon simply because radon is naturally present.

Public Health Significance

Radon is recognized internationally as an important environmental risk factor because prolonged exposure to elevated concentrations is associated with increased lung-cancer risk. The presence of radon in indoor environments is therefore an environmental health issue even when average concentrations are relatively low.

For Chandigarh, the currently published evidence does not indicate widespread extremely elevated indoor radon concentrations. However, the substantial variation among dwellings and the relatively high thoron concentrations observed in some measurements justify continued surveillance.

Public-health communication should avoid unnecessary alarm. Radon is a naturally occurring gas, and its presence indoors does not automatically mean that a dwelling presents an immediate danger. Instead, the appropriate approach is measurement, risk assessment and mitigation where concentrations are found to be elevated.

Limitations of Existing Chandigarh Studies

Although the published Chandigarh investigations provide valuable information, several limitations should be considered.

First, the number of dwellings investigated in individual studies was relatively limited compared with the total residential population of Chandigarh. Consequently, the results cannot automatically be treated as a complete city-wide distribution.

Second, different studies used different detector systems and sampling periods. Differences in calibration, exposure duration and sampling season may contribute to differences in measured concentration.

Third, detailed information on every building characteristic is not always available. Variables such as floor level, floor material, wall material, foundation construction, room volume and occupancy pattern could improve statistical interpretation.

Fourth, thoron is particularly difficult to characterize because of its short half-life and spatial gradients. A detector location close to a thorium-containing wall may record a significantly different concentration from one positioned in the centre of the room.

Finally, a small number of seasonal observations may not fully represent long-term annual exposure.

Recommendations for Future Research

A comprehensive Chandigarh radon-thoron monitoring programme should include the following components.

Larger Sample Size

A substantially larger number of dwellings should be sampled across different sectors and building types to establish a representative city-wide distribution.

Seasonal Monitoring

Measurements should be conducted during summer, monsoon, autumn and winter to establish seasonal patterns.

Long-Term Measurements

Long-duration passive detectors should be used to estimate annual average indoor concentrations.

Radon-Thoron Discrimination

All future surveys should distinguish ^222Rn from ^220Rn rather than reporting a combined alpha-track response.

Building Characterization

Information should be recorded on:

- building age;
- construction material;
- floor level;
- foundation type;
- room dimensions;
- floor material;
- wall material;
- ventilation;
- number of windows;
- occupancy;
- air-conditioning use.

Soil and Building Material Analysis

Soil samples and commonly used construction materials should be analysed for uranium, thorium and radium concentrations as well as radon/thoron exhalation rates.

GIS-Based Mapping

Geographical Information System techniques could be used to create Chandigarh-specific radon and thoron distribution maps. Such maps could integrate geological, soil, construction and building information.

Continuous Monitoring

Selected representative dwellings should be monitored using active continuous radon monitors to investigate hourly and daily variations.

Dose Assessment

Future investigations should include radon and thoron progeny measurements wherever possible so that inhalation dose can be estimated more directly.

Proposed Research Framework for Chandigarh

A future large-scale investigation could divide Chandigarh into representative sampling zones based on geographical and residential characteristics.

For each selected dwelling, a radon-thoron discriminating passive detector could be installed in an occupied room for approximately three months per season. The detector should be positioned away from direct sunlight, excessive moisture and unusual airflow.

Simultaneously, environmental parameters such as temperature, relative humidity and ventilation conditions should be recorded.

Soil samples should be collected from locations surrounding selected buildings, where appropriate, and analysed for radium concentration and radon exhalation.

Building materials such as sand, bricks and cement-related materials could also be characterized for uranium and thorium content.

The resulting database could then be analysed statistically to determine:

$$C_{Rn} = f(S, V, B, M, T)$$

where:

- C_{Rn} = indoor radon concentration;
- S = soil source characteristics;
- V = ventilation;
- B = building characteristics;
- M = construction materials;

- T = temporal/seasonal conditions.

A similar model could be developed for thoron, but with additional emphasis on source-surface distance and thorium-bearing construction materials.

Overall Interpretation

The published evidence indicates that Chandigarh is characterized by detectable but generally moderate indoor radon concentrations, together with significant variability in indoor thoron.

The first major Chandigarh investigation reported an average indoor radon concentration of 23.3 Bq m^-3 and an average thoron concentration of 10.7 Bq m^-3. The annual effective dose averaged approximately 0.8 mSv.

A later investigation reported higher average values, approximately 39.9 Bq m^-3 for radon and 31.1 Bq m^-3 for thoron, with maximum concentrations of 62.1 Bq m^-3 and 99.2 Bq m^-3, respectively.

The difference between these investigations should not automatically be interpreted as a temporal increase in Chandigarh's radiation levels. The studies used different samples and methodologies, and therefore the differences may arise from sampling and environmental variability.

The most important conclusion is that Chandigarh cannot be represented by a single universal radon or thoron concentration. Individual dwellings exhibit substantial variation.

Conclusion

The investigation of indoor radon and thoron in Chandigarh demonstrates the importance of assessing naturally occurring radioactive gases as components of indoor environmental quality. Published measurements show that ^222Rn is present in Chandigarh dwellings at concentrations ranging from low single-digit values to more than 60 Bq m^-3 in the investigated datasets. Thoron exhibits even greater variability, with measurements ranging from near-detection-limit concentrations to approximately 100 Bq m^-3 in some dwellings. The average radon concentration of 23.3 Bq m^-3 reported in one Chandigarh study is close to the overall Indian geometric mean reported in a nationwide review, while the later Chandigarh dataset produced a higher mean of approximately 39.9 Bq m^-3. The available evidence suggests that indoor radon exposure in the studied Chandigarh dwellings was generally moderate. The reported annual effective dose of 0.3–1.4 mSv, with an average of approximately 0.8 mSv in one investigation, further indicates that the studied dwellings did not exhibit an exceptionally high radiological burden.

Nevertheless, the substantial variation in thoron concentrations deserves particular attention. Thoron can make an important contribution to indoor exposure in certain environments, and its short half-life causes its concentration to depend strongly on source location and building materials. Consequently, surveys based exclusively on radon may underestimate or mischaracterize the total exposure environment. Soil exhalation measurements further demonstrate that the ground can act as a source of radon, while construction materials can contribute to both radon and thoron depending on their natural radionuclide content and emanation characteristics.

Overall, the Chandigarh evidence supports a strategy based on measurement rather than assumption. Large-scale seasonal surveys, radon-thoron discriminating detectors, soil and construction-material characterization, building surveys and GIS-based mapping would provide a more complete picture of residential radiation exposure.

A systematic Chandigarh radon-thoron database would be valuable for environmental radiation protection, urban planning and public-health research. Particular attention should be given to dwellings showing unusually high thoron or radon concentrations, while maintaining a balanced interpretation that recognizes the generally moderate levels reported in existing studies.

Suggested Future Work

Future research should aim to establish a statistically representative Chandigarh radon-thoron map based on measurements from a substantially larger number of dwellings. The study should combine passive and active detector technologies. Passive SSNTDs can provide long-term integrated concentrations, whereas continuous monitors can reveal short-term fluctuations and relationships with ventilation and meteorological conditions.

A further important research direction is the characterization of construction materials. Chandigarh's residential buildings use a wide variety of mineral-based materials, and their uranium, thorium and radium content may differ substantially. Measurement of radon and thoron exhalation from these materials could help identify the dominant indoor sources. Finally, future studies should integrate radiation measurements with environmental parameters and building characteristics. Such multidisciplinary research would allow more reliable identification of homes requiring further assessment and could support evidence-based radiation-protection recommendations.

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6. Published Chandigarh SSNTD measurements have additionally reported individual-dwelling radon values of approximately 14.9–34.2 Bq m^-3 in one dataset, illustrating the variability observed between homes.

Key Findings at a Glance

The principal findings of the published Chandigarh research can be summarized as follows:

Radon: approximately 7.9–62.1 Bq m^-3 across the reported datasets.

Thoron: approximately 0.15–99.2 Bq m^-3 across the reported datasets.

Mean radon: 23.3 Bq m^-3 in the earlier investigation and approximately 39.9 Bq m^-3 in the later investigation.

Mean thoron: 10.7 Bq m^-3 in the earlier investigation and approximately 31.1 Bq m^-3 in the later investigation.

Annual effective dose: 0.3–1.4 mSv, with an average of approximately 0.8 mSv in the earlier Chandigarh study.

Mean soil radon mass exhalation: approximately 1.39 ± 0.29 mBq kg^-1 h^-1.

Mean soil radon surface exhalation: approximately 31.4 ± 6.8 mBq m^-2 h^-1.

The overall evidence suggests that Chandigarh's investigated dwellings generally exhibit moderate indoor radon concentrations, while thoron can show considerable local variability.