

Indoor Radon Exposure and Age-Dependent Lung Retention Modelling in Murang'a County, Kenya

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Received 28-07-2026

Accepted for publication 25-09-2026

Published 06-10-2026

Abstract

Indoor radon (^{222}Rn), from the ^{238}U decay chain via ^{226}Ra is a major natural radiation source and a recognized lung carcinogen through inhalation of its short-lived alpha-emitting progeny, particularly ^{218}Po and ^{214}Po . This study quantified indoor radon concentrations in Murang'a County, Kenya, and modelled age-dependent respiratory deposition, retention (lung inventories), and annual effective doses using the International Commission on Radiological Protection (ICRP) Human Respiratory Tract Model (HRTM). Radon concentrations were measured in 30 residential houses using a RAD7 detector, with values ranging from 9.74 to 54.23 Bq m⁻³. The verified dataset was used consistently for the concentration, inventory, and dose analyses. The revised computational model incorporated the 11-compartment HRTM structure of ICRP Publication 130, with the age-dependent dosimetric framework and home-radon dose coefficients of ICRP Publication 158. The three study groups were mapped to the ICRP reference ages of 3 months, 10 years, and adult. An equilibrium factor of 0.4 and age-specific mean home breathing rates of 0.12, 0.56, and 0.78 m³ h⁻¹ for infants, children, and adults, respectively, were applied. The model explicitly tracked the decay chain $^{218}\text{Po} \rightarrow ^{214}\text{Pb} \rightarrow ^{214}\text{Bi} \rightarrow ^{214}\text{Po}$ and was solved numerically in Python using the BDF method. Lung inventories increased with indoor radon concentration and approached quasi-steady conditions within the simulated exposure period. Adults exhibited the highest retained physical lung inventories, whereas infants had the highest modelled annual effective doses. Mean progeny-only annual effective doses were 1.060, 0.830, and 0.811 mSv y⁻¹ for infants, children, and adults, respectively. The highest estimated infant dose occurred in House 8, which had the highest measured radon concentration of 54.23 Bq m⁻³. All radon concentration measurements obtained were lower than the reference values established by WHO and ICRP. These data show age-related variations in respiratory retention and radiation dose modelling and represent a quantitative basis for indoor radon exposure assessment in Murang'a County.

Keywords: Indoor radon; RAD7 detector; Respiratory deposition model; Effective dose; Murang'a County.

I. INTRODUCTION

Radon gas (^{222}Rn), an inert noble gas, is formed through the radioactive decay of radium (^{226}Ra), which is one of the decay products of the ^{238}U decay chain. Radon is an odourless,

colourless, and chemically inert gas that enters buildings by seeping through pores and cracks in the ground [1]. The accumulation of radon gas indoors is influenced by several factors, including geology, soil porosity, weather conditions, ventilation rates, and the architectural design of buildings.

Radon concentrations are also influenced by seasonal variations, with higher levels occurring during the cold season [2–3].

The radiobiological effects of radon primarily result from its radioactive progeny, ^{218}Po and ^{214}Po , which emit high-LET α -particles. When inhaled, these alpha particles cause tissue damage through localized irradiation. Radon progeny bind to aerosols and dust particles, which are inhaled and deposited in different parts of the respiratory tract, potentially causing tissue damage. The effects of alpha particles on lung tissues, including DNA strand breaks, mutations, and oxidative damage, contribute to carcinogenesis by inducing cellular changes and abnormal cell proliferation. The accumulation, clearance, and retention of radon decay products are affected by age because of differences in lung structure and breathing patterns among individuals [4–5].

Numerous epidemiological studies have revealed a link between prolonged radon exposure and an increased risk of lung cancer [1]. Radon is the second leading cause of lung cancer globally after tobacco smoking [1]. World Health Organization (WHO) estimates indicate that radon contributes to 3–14% of global lung cancer mortality, depending on national exposure and smoking rates [6]. This threat is intensified by simultaneous smoking owing to the combined retention and harmful effects of particles and α -radiation [7]. Current research focuses on the genetics of radon-induced cancers, including tumour suppressors, oncogenes, and inflammatory and oxidative stress markers [8].

The inhalation dose depends on the concentration, size distribution, and proportion of unattached progeny in the inhaled radon progeny. According to the dose coefficients, the maximum radiation dose to the lungs is caused by polonium nuclides, namely ^{214}Po and ^{218}Po [4]. Models of age-specific aerosol retention in the respiratory system suggest that infants and children may receive higher doses because of differences in respiratory characteristics and deposition patterns [4–5].

Assessing the risk of radon-induced lung cancer across populations requires consideration of age-related respiratory characteristics and exposure scenarios. Infants and children require specialized dosimetric models for precise evaluation owing to their greater radiosensitivity and distinct deposition patterns [4–5]. Although the issue of indoor radon in sub-Saharan Africa is increasingly receiving attention, no previous study has undertaken modelling of age-specific lung dosimetry in Kenyan houses. The purpose of this study was to (a) determine indoor radon levels in residential buildings in Murang'a County, Kenya; (b) model age-specific deposition, retention, and dosimetry of radon progeny using the ICRP HRTM; and (c) compare annual effective doses among infants, children, and adults.

II. MATERIALS AND METHODS

A. Study Area

The experiment was carried out in Murang'a County,

located in the central part of Kenya. The area is known for its diverse geological conditions and high population density. Different kinds of houses used in this study include permanent, semi-permanent, and indigenous traditional houses. The aim of using different kinds of houses in this study was to compare indoor radon levels across building types. The construction materials of permanent buildings included stone, concrete, and cement mortar. Also, the permanent houses had tiled or cemented flooring and metal sheet roofing. These buildings were considered new since they were constructed following modern designs and had been built with surface floors. Semi-permanent buildings were built using wood and bricks while having metal sheet roofing and cemented floor surfaces. Traditional houses are mud- or wood-walled with iron sheet roofing and earthen floors.

B. Research Design and Sampling Strategy

To determine the level of radon inside the houses in Murang'a County, a descriptive cross-sectional survey was performed. Stratified purposive sampling was used to sample 30 houses from the three types. The 30 sampled houses included 14 permanent ($\cong 46.7\%$), 8 semi-permanent ($\cong 26.7\%$), and 8 traditional ($\cong 26.7\%$) houses. The geographic coordinates of each sampling site were documented using global positioning system (GPS) technology as shown in Fig. 1.

C. Indoor Radon Measurement

The indoor concentration of radon was determined using a RAD7 detector. The detector was placed in the living rooms at a height of 1 m from the floor in all the houses and positioned in such a way as to be sufficiently shielded against air movement, as well as from being in contact with any walls. The measurement time for each sampled house was 8 h. To ensure precision and uniformity of radon measurements, a desiccator with anhydrous calcium sulfate was used to continuously eliminate any moisture from the air sample prior to its detection with the RAD7 apparatus. High moisture content could affect the process of electrostatic collection of positively charged radon progeny, hence affecting the reliability of the results. The desiccant maintained a relative humidity level below the recommended manufacturer level of 10%.

D. Respiratory Deposition and Biokinetic Modelling of Radon Progeny

The inhalation and retention of radon progeny within the human respiratory tract were modelled using the Human Respiratory Tract Model (HRTM) created by the International Commission on Radiological Protection (ICRP) [9]. The Human Respiratory Tract Model (HRTM) describes the mechanism of aerosol transport within the respiratory tract and has become a widespread approach for internal dosimetry modelling. Because HRTM considers physiological properties depending on age, it allows the assessment of radon progeny inhalation and retention in infants, children, and adults [9].

The first stage of the modelling involved estimating the radon progeny activity inhaled into the body by a person. The radon concentration indoors obtained using the RAD7 instrument was the primary data source. An equilibrium factor of 0.4 was used based on the WHO recommendations [6] and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [10]. The inhalation intake was estimated using (1).

$$I = C_{air} \cdot B \cdot F \quad (1)$$

where (I) represents the rate of intake (Bq h^{-1}), C_{air} the measured value of indoor radon concentration (Bq m^{-3}), (B) the breathing rate ($\text{m}^3 \text{h}^{-1}$), and (F) the equilibrium factor. Age-

specific breathing rates of 0.12, 0.56, and $0.78 \text{ m}^3 \text{h}^{-1}$ were used in this study for infants, children, and adults, respectively [11]. Occupancy times per year of 8030 h y^{-1} for infants and 4745 h y^{-1} for children and adults, which were used in this study design, are considered study-specific parameters and not ICRP parameters (Table I).

For the aerosols in home conditions, the aerosol parameterization included a fraction of unattached $f_p = 0.10$, an attached fraction $f_{pn} = 0.20$, an unattached mode of 1 nm, a nucleation mode of 30 nm, an accumulation mode of 200 nm, and a hygroscopic factor of 1.75 (Table II) [11–12].

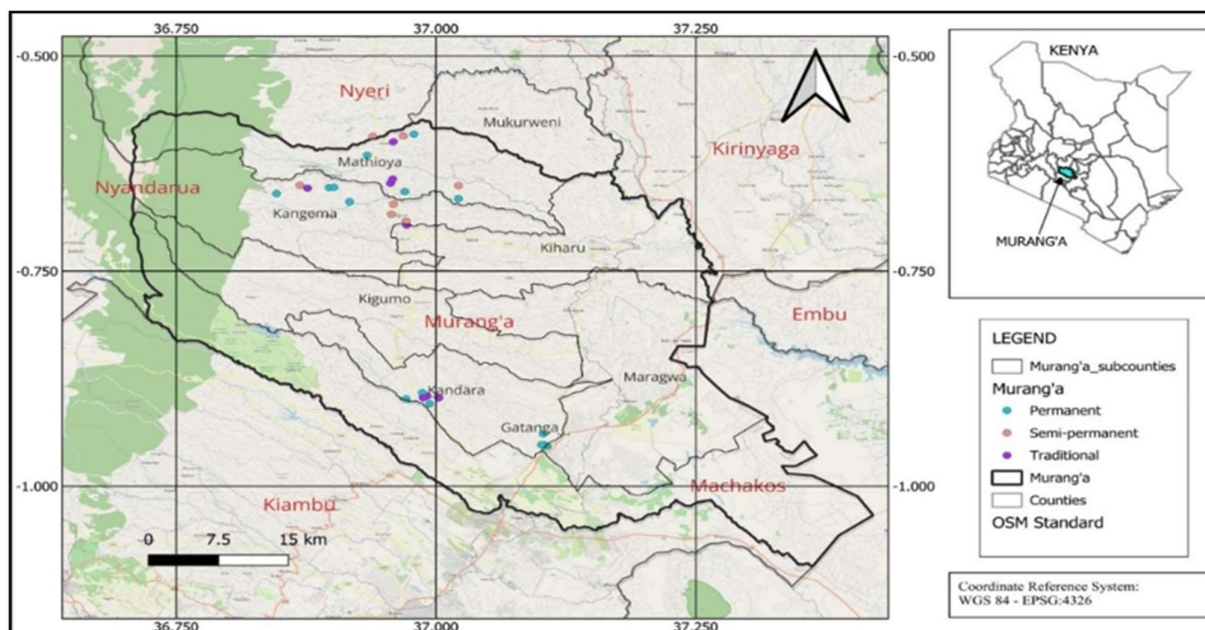


Fig. 1. Map showing the spatial distribution of the sampled residential houses in Murang'a County, Kenya, used for indoor radon measurements and lung inventory modelling.

Table I. Reference physiological and exposure parameters.

Parameter	Infant	Child	Adult	Unit	Status/source
ICRP reference age	3 months	10 years	Adult	—	[11]
Mean home breathing rate	0.12	0.56	0.78	$\text{m}^3 \text{h}^{-1}$	[11]
Annual occupancy	8030	4745	4745	h y^{-1}	Study-specific
Equilibrium factor, F	0.40	0.40	0.40	dimensionless	Table 32.2, [11]
AI target-tissue mass	0.0904	0.497	1.100	kg	Table 2.8, [11]

Table II. Radon-progeny aerosol parameters.

Parameter	Value	Unit	Source
Equilibrium factor, F	0.40	dimensionless	Table 32.2, [11]
Unattached fraction, f_p	0.10	dimensionless	Table 32.2, [11]
Attached nucleation fraction, f_{pn}	0.20	dimensionless	Table 32.2, [11]
Unattached AMTD	1	Nm	deposition parameter, [11]
Nucleation-mode AMTD	30	Nm	Table 32.2, [11]
Accumulation-mode AMTD	200	Nm	Table 32.2, [11]
Unattached mode weight	0.10	dimensionless	Calculated from f_p
Attached nucleation weight	0.18	dimensionless	Calculated from $(1 - f_p)f_{pn}$
Attached accumulation weight	0.72	Dimensionless	Calculated from $(1 - f_p)(1 - f_{pn})$
Hygroscopic growth factor	1.75	Dimensionless	Table 32.2, [11]

Fig. 2 presents the 11-compartment HRTM used in this study. This model is based on the respiratory-tract model

described in ICRP Publication 130 [12] and uses the age-specific dosimetric model of ICRP Publication 158 [11].

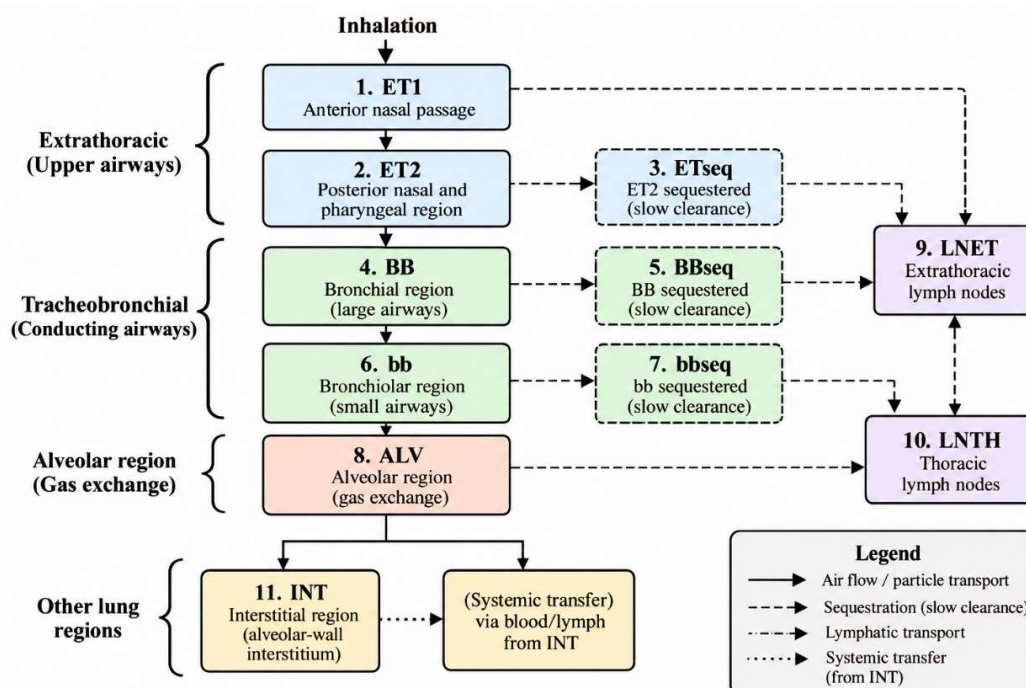


Fig. 2. Schematic depiction of the 11-compartment Human Respiratory Tract Model (HRTM) developed to assess the inhalation, deposition, transport, retention, and elimination of radon progeny. The compartments of the model include ET1 (anterior nasal passage), ET2 (posterior nasal and pharyngeal area), ETseq (sequestered extra thoracic material), BB (bronchial area), BBseq (sequestered bronchial material), bb (bronchiolar area), bbseq (sequestered bronchiolar material), ALV (alveolar area), INT (interstitial area), LNET (extra thoracic lymph nodes), and LNTH (thoracic lymph nodes). Transport of particles through the respiratory tract is shown using solid arrows, and sequestration and lymphatic transport using dashed lines.

The regional deposition fractions, which are dependent on age and aerosol size, have been incorporated in the model. The regional deposition fraction of the age group was calculated by the product of the deposition fractions of 1 nm, 30 nm, and 200 nm aerosol modes and their weights (Table II). The deposition fractions are shown in Table III. These are regional

deposition efficiencies and not fractions of total inhaled aerosol; they must add up to one. Hence, the total of regional deposition fractions is the total fraction of inhaled aerosol deposited in the modeled respiratory regions, and the rest is the fraction of aerosol that is not deposited and gets exhaled [11], [13].

Table III. Age- and aerosol-size-specific regional deposition fractions.

Age group	AMTD (nm)	ET1	ET2	BB	Bb	AI
Infant (3 months)	1	0.5484	0.2953	0.1184	0.02594	0.000137
Infant (3 months)	30	0.04442	0.02392	0.02818	0.1140	0.2856
Infant (3 months)	200	0.1030	0.05544	0.009478	0.03018	0.09916
Child (10 years)	1	0.5285	0.2846	0.08812	0.07748	0.003719
Child (10 years)	30	0.04380	0.02359	0.01369	0.08264	0.2768
Child (10 years)	200	0.07240	0.03899	0.005580	0.02041	0.08709
Adult	1	0.5268	0.2837	0.08436	0.08438	0.004072
Adult	30	0.04297	0.02314	0.01237	0.08207	0.2942
Adult	200	0.05416	0.02916	0.004952	0.02082	0.09546

The deposited activity does not remain stationary in the lungs. Following deposition, radionuclides undergo a series of competing processes, including radioactive decay,

mucociliary transport, absorption into the blood, and transfer between neighboring respiratory compartments. A compartmental biokinetic model was used to quantitatively

describe these processes in the HRTM model. Each respiratory compartment was represented as a dynamic reservoir in which radionuclide activity changed continuously over time, owing to the gains and losses of radionuclide activity. [9], [14–16]

The temporal evolution of radionuclide activity in each respiratory compartment was described using the system of coupled differential equations recommended by the ICRP [14], consistent with contemporary biokinetic modelling frameworks based on compartmental ordinary differential equations in (2) [14–15], [17].

$$\frac{dA_{ir}}{dt} = S_{ir}(t) + \sum_j k_{ji} A_j r - [\sum_j k_{ij} + \lambda_r + k_{abs,r}] A_{ir} \quad (2)$$

Here, $S_{ir}(t)$ is the deposition/source term, k_{ji} and k_{ij} are inter-compartmental transfer parameters (Table IV), λ_r is the radioactive decay constant (Table V), and $k_{abs,r}$ is the absorption/removal rate. This decay chain for $^{218}\text{Po} \rightarrow ^{214}\text{Pb} \rightarrow ^{214}\text{Bi} \rightarrow ^{214}\text{Po}$ was considered in detail. Thus, A in the compartment equation refers to the activity of an individual radionuclide in a single compartment; total lung inventory is obtained by summing the relevant radionuclide and lung-compartment activities.

The physical decay constants of radionuclides were computed based on their half-lives using (3).

$$\lambda_r = \frac{\ln(2)}{T_{1/2}} \quad (3)$$

Table IV. Revised HRTM particle-transport parameters.

Source	Destination	Rate (d ⁻¹)	Process
ET1	Environment	0.600	Extrathoracic clearance
ET1	ET2	1.500	Particle transport
ET2	Oesophagus	100	Short-term ET2 clearance
BB	ET2	10	Bronchial particle transport
Bb	BB	0.200	Bronchiolar particle transport
ETseq	LNET	0.001	Sequestered ET clearance
BBseq	LNTH	0.001	Sequestered BB clearance
Bbseq	LNTH	0.001	Sequestered bb clearance
ALV	Bb	0.002	Alveolar particle transport
ALV	INT	0.001	Alveolar-interstitial transfer
INT	LNTH	0.00003	Interstitial clearance
ET2/BB/bb	Airway wall	0.002	Sequestered fraction (0.2%)

0.002 for ET2/BB/bb is a fraction (0.2%) and not a first-order transfer coefficient; hence, it was considered a deposition/sequestration fraction and not a transfer rate.

Table V. Radionuclide decay and absorption parameters.

Radionuclide	Half-life	Decay constant (s ⁻¹)	F _r	S _r (d ⁻¹)	S _s (d ⁻¹)	F _b	S _b (d ⁻¹)
^{218}Po	3.10 min	3.72660e-03	1.0	3.0	—	0	—
^{214}Pb	26.8 min	4.31062e-04	0.1	100	1.7	0.5	1.7
^{214}Bi	19.9 min	5.80525e-04	1.0	1.0	—	0	—
^{214}Po	164.3 μs	4.21879e+03	—	—	—	—	—

The parameters for the absorption of radon progeny by inhalation were obtained from ICRP Publication 158 [11]. The parameters f_r , s_r , s_s , f_b and s_b refer to the fractions and rates involved in the fast and slow absorption pathways (Table V). In the case of ^{218}Po and ^{214}Bi , the parameterization provided uses only a fast pathway. There were no absorption parameters for ^{214}Po due to its very short half-life. [11], [15].

The coupled ordinary differential equations were solved numerically using Python, NumPy, and SciPy. The model had 11 respiratory-tract HRTM compartments and 4 radon progeny being tracked, making for 44 dynamic variables in total. A stiff implicit solver was used since the system includes processes operating on different time scales, especially the very short lifetime of ^{214}Po and the slower lung transport processes. Numerical integration was done with a relative tolerance of 1×10^{-8} and an absolute tolerance of 1×10^{-12} . The lung inventory calculation was run over the duration of

the exposure, and the results presented are those from the 12-hour run used for inventory curves.

E. Annual Effective Dose Estimation

The lung mass-normalized absorbed dose equation was kept as a supplementary mechanism-based dosimetry model to estimate the energy deposition in respiratory tract tissues and make comparisons of energy deposition based on age dependence [18]. This approach was not used for calculation of annual effective dose estimates listed in Table X. The absorbed dose to lung tissue is defined as in (4).

$$D = \frac{E}{m} \quad (4)$$

where D is the absorbed dose in Gy, E is the energy deposited within the lung tissue in joules, and m is the corresponding target-tissue mass in kilograms [10], [18].

The target-tissue masses employed in this study for the respiratory model were 0.0904 kg for the infant alveolar-interstitial region, 0.497 kg for the child, and 1.100 kg for the

adult. To estimate the annual effective dose, the age-dependent ICRP Publication 158 effective dose coefficients associated with home exposure to radon were employed. ICRP Publication 158 includes the effective dose coefficients for the

inhalation of radon gas alone, aerosols of radon progeny, and the combination of both. For the present study, the coefficient for aerosol inhalation alone has been employed for the primary values presented in Table IV [11], [18–19].

Table VI. ICRP Publication 158 home-radon effective-dose coefficients used in the annual dose calculation.

Reference age	Progeny only	Gas + progeny	Unit
3 months	7.20×10^{-6}	7.30×10^{-6}	mSv per Bq h m ⁻³
10 years	9.54×10^{-6}	9.70×10^{-6}	mSv per Bq h m ⁻³
Adult	9.32×10^{-6}	9.50×10^{-6}	mSv per Bq h m ⁻³

The annual effective dose, H_E , was calculated using (5).

$$H_E = C \cdot T \cdot DC \quad (5)$$

where H_E is the annual committed effective dose in mSv y⁻¹, C is the measured indoor radon concentration in Bq m⁻³, T is the annual indoor occupancy time in h y⁻¹, and DCF is the corresponding ICRP Publication 158 home-radon effective-dose coefficient in mSv per Bq h m⁻³.

The reference-age mapping was applied consistently as follows: infant to 3 months, child to 10 years, and adult to adult. The annual occupancy times used were 8030 h y⁻¹ for infants and 4745 h y⁻¹ for children and adults.

In addition, it should be mentioned that lung-mass-normalized absorbed-dose and ICRP Publication 158 effective-dose calculations refer to the two separate yet related elements of the research. In particular, the first one refers to the actual energy imparted to respiratory tissues according to the modeled radionuclide inventories, while the second one refers to the effective dose value stated in Table X. Thus, lung mass is not considered as a normalizer in the calculation of the annual ICRP Publication 158 effective doses.

F. Extrapolation from the 8-h RAD7 Measurement to Annual Exposure

Indoor radon concentration was continuously measured in each sampled dwelling for 8 h via the RAD7 detector. The 8-hour measurement was utilized to calculate the mean indoor

radon concentration, C , in each sampled house. The annual dose was not calculated based on the assumption that the 8-hour dose equals 1-year exposure to indoor radon. Rather, the 8-hour measurement was considered an estimate of representative indoor radon concentration that is used together with annual occupancy time in the ICRP Publication 158 dose coefficient formula.

To make this clearer, the 8-hour measurement dose is given as

$$H_{E,8} = C (8 \text{ h}) DCF \quad (6)$$

Assuming the 8-hour mean concentration as representative of concentration during annual occupancy time T , the annual effective dose is calculated using (7).

$$H_{E,y} = H_{E,8} \times \left(\frac{T}{8h} \right) \quad (7)$$

Equation (9) is obtained by substituting (6) into (7).

$$H_{E,y} = C (8 \text{ h}) DCF \times \left(\frac{T}{8h} \right) = C \cdot T \cdot DCF \quad (9)$$

The 8-hour measurement time is mathematically cancelled and only serves to find the representative value of C . Thus, the annualization factor becomes $T/8$ instead of $365/8$, an arbitrary factor. The corresponding value for infant reference age is $T = 8030 \text{ h y}^{-1}$, so the corresponding scaling factor is $8030/8 = 1003.75$. The same for children and adults is 4745 h y^{-1} , and the corresponding factor is $4745/8 = 593.125$. The scaling factors are tabulated in Table VII.

Table VII. Annualization factors applied to the 8-h measurements.

Reference group	Annual occupancy (h y ⁻¹)	Equivalent 8-h periods y ⁻¹
Infant (3 months)	8030	1003.75
Child (10 years)	4745	593.125
Adult	4745	593.125

III. RESULTS AND DISCUSSION

A. Indoor Radon Concentrations

Table VIII shows that radon concentrations measured in the 30 sampled houses ranged from 9.74 to 54.23 Bq m⁻³, with the lowest concentration recorded in House 28 and the highest in House 8. The validated final dataset was used consistently for the concentration, lung inventory, and annual dose calculations.

The highest concentration was measured in House 8 (54.23 Bq m⁻³), House 24 (49.55 Bq m⁻³), House 1 (38.36 Bq m⁻³), and House 23 (30.47 Bq m⁻³). It is important to note that

Houses 23 and 24 are categorized as traditional houses, which shows that this type of construction does not necessarily dictate the radon concentration in houses [1], [6].

The average radon concentration for the group of permanent houses was 19.08 Bq m⁻³ (SD = 12.55; Median = 13.28; Range = 9.74 – 54.23 Bq m⁻³), whereas for semi-permanent houses, it was 14.94 Bq m⁻³ (SD = 3.28; Median = 14.28; Range = 10.97 – 19.93 Bq m⁻³). The average radon concentration for traditional houses was 20.42 Bq m⁻³ (SD = 13.21; median = 14.50; range = 11.21 – 49.55 Bq m⁻³).

As the number of houses for each type is relatively small and there is a lot of within-group variability, the Kruskal-

Wallis test was applied. No statistically significant difference among permanent, semi-permanent, and traditional houses ($H = 0.440$, $p = 0.802$) was found. One-way ANOVA gives the

same result ($F(2, 27) = 0.543$, $p = 0.587$). Thus, the differences between housing categories are described and can be considered a non-significant housing-type effect.

Table VIII. Indoor radon concentrations measured in the sampled residential houses together with corresponding housing characteristics.

House	House Design	House Characteristics	Mean (Bq m^{-3})
House 1	Permanent	Basement floor, tiled block house	38.36
House 2	Permanent	Tiled modern block house	17.62
House 3	Permanent	Tiled modern block house	11.64
House 4	Traditional	Earthen floor mud house	13.43
House 5	Semi-permanent	Tiled floor wooden house	19.93
House 6	Semi-permanent	Iron sheet and cemented floor	12.84
House 7	Semi-permanent	Wooden and cemented floor	11.61
House 8	Permanent	Permanent, cemented floor	54.23
House 9	Traditional	Earthen floor mud house	11.21
House 10	Permanent	Permanent concrete and tiled floor	12.05
House 11	Permanent	Tiled block modern house	13.89
House 12	Semi-permanent	Cemented, wooden house	17.82
House 13	Semi-permanent	Cemented iron sheet house	17.80
House 14	Traditional	Earthen floor, iron sheets	13.69
House 15	Traditional	Earthen floor, wooden house	13.28
House 16	Traditional	Earthen floor, mud house	16.41
House 17	Permanent	Tiled block house	12.66
House 18	Semi-permanent	Cemented brick house	13.32
House 19	Semi-permanent	Cemented floor, wooden house	10.97
House 20	Permanent	Modern storey tiled house	25.19
House 21	Permanent	Tiled block modern house	18.11
House 22	Permanent	Cemented, block house	12.17
House 23	Traditional	Earthen floor mud house	30.47
House 24	Traditional	Earthen floor, iron sheets	49.55
House 25	Semi-permanent	Cemented, wooden house	15.24
House 26	Traditional	Earthen floor, wooden house	15.30
House 27	Permanent	Tiled modern block house	16.33
House 28	Permanent	Tiled block modern house	9.74
House 29	Permanent	Tiled modern block house	12.51
House 30	Permanent	Cemented, block house	12.55

Relatively high radon concentrations in some permanent houses seem to be caused by their enclosed design, floor characteristics, and low air exchange. Nevertheless, relatively high concentrations in traditional houses, particularly in Houses 23 and 24, show that these factors cannot be considered separately from the area's geological and environmental conditions. Such variability of indoor radon can be explained by building characteristics, ventilation, and time factors [2–3], [20–21].

All measured concentrations of radon are below the WHO reference level of 100 Bq m^{-3} and the ICRP reference level of 300 Bq m^{-3} [6], [22].

B. Lung Inventory

In the simulation results using 11 compartments, there is a consistent trend for the radon concentration and the terminal lung inventory in HRTM (Table IX). The houses with high radon concentrations generally resulted in high lung inventories for each reference age. This is because the more

the ambient radon concentration increases, the more the availability of the progeny for inhalation and deposition, where radioactive decay and respiratory clearance determine the lung inventories [9], [14].

In House 8, which recorded the highest radon concentration (54.23 Bq m^{-3}), the inventories were 0.5056 Bq for infants, 2.0506 Bq for children, and 3.0169 Bq for adults. For House 24, which had a concentration of 49.55 Bq m^{-3} , the inventories were 0.4619 , 1.8736 , and 2.7566 Bq for infants, children, and adults. On the other hand, House 28 had a concentration of 9.74 Bq m^{-3} , resulting in 0.0908 , 0.3683 , and 0.5419 Bq for infants, children, and adults.

Adults have the largest physical lung inventories, followed by the children and then the infants. This was because of the higher breathing rate volume of the adults, resulting in higher inhaled activity. This does not mean that the adults receive the highest effective doses from the exposure. This is because lung inventory, absorbed dose, and the effective dose are different and cannot be compared.

The model has been designed in such a way that it tracks the radionuclides ^{218}Po , ^{214}Pb , ^{214}Bi , and ^{214}Po throughout the decay series $^{218}\text{Po} \rightarrow ^{214}\text{Pb} \rightarrow ^{214}\text{Bi} \rightarrow ^{214}\text{Po}$. This implies that

the reported lung inventories are the total activities of the progeny in the lungs' compartments.

Table IX. Steady-state radon progeny inventories for infants, children, and adults in Houses 1–30 under continuous indoor exposure conditions.

House	Radon (Bq m^{-3})	Infant (Bq)	Child (Bq)	Adult (Bq)
1	38.36	0.3576	1.4505	2.1341
2	17.62	0.1643	0.6663	0.9802
3	11.64	0.1085	0.4401	0.6476
4	13.43	0.1252	0.5078	0.7471
5	19.93	0.1858	0.7536	1.1087
6	12.84	0.1197	0.4855	0.7143
7	11.61	0.1082	0.4390	0.6459
8	54.23	0.5056	2.0506	3.0169
9	11.21	0.1045	0.4239	0.6236
10	12.05	0.1123	0.4557	0.6704
11	13.89	0.1295	0.5252	0.7727
12	17.82	0.1661	0.6738	0.9914
13	17.80	0.1659	0.6731	0.9903
14	13.69	0.1276	0.5177	0.7616
15	13.28	0.1238	0.5022	0.7388
16	16.41	0.1530	0.6205	0.9129
17	12.66	0.1180	0.4787	0.7043
18	13.32	0.1242	0.5037	0.7410
19	10.97	0.1023	0.4148	0.6103
20	25.19	0.2348	0.9525	1.4014
21	18.11	0.1688	0.6848	1.0075
22	12.17	0.1135	0.4602	0.6770
23	30.47	0.2841	1.1522	1.6951
24	49.55	0.4619	1.8736	2.7566
25	15.24	0.1421	0.5763	0.8478
26	15.30	0.1426	0.5785	0.8512
27	16.33	0.1522	0.6175	0.9085
28	9.74	0.0908	0.3683	0.5419
29	12.51	0.1166	0.4730	0.6960
30	12.55	0.1170	0.4746	0.6982

C. The Inventory Curves

The modeled inventory curves shown in Fig. 3, 4, and 5 show that radon progeny rapidly accumulate at the start of exposure before reaching a quasi-steady state. The approximate equilibration duration of 3–4 hours is attributed to the brief radioactive half-life of the primary progeny and the relatively rapid mechanisms of respiratory transport. The influence of slower transfer pathways can be seen in the approach to equilibrium. [13], [16], [23].

The houses 8, 20, and 28 were selected for Figs. 3, 4, and 5 to illustrate the high, medium, and low concentrations of radon measured in these buildings (54.23, 25.19, and 9.74 Bq m^{-3} , respectively). The impact of exposure concentration on the total accumulated activity may be observed without altering the age-dependent framework of the model.

The higher adult inventories in the curves indicate higher amounts of the physical activity retained in the model under the specific conditions. These values cannot be used as an

indicator of the health risk directly because the effective dose depends on other age-related dosimetric factors. [11], [16], [23].

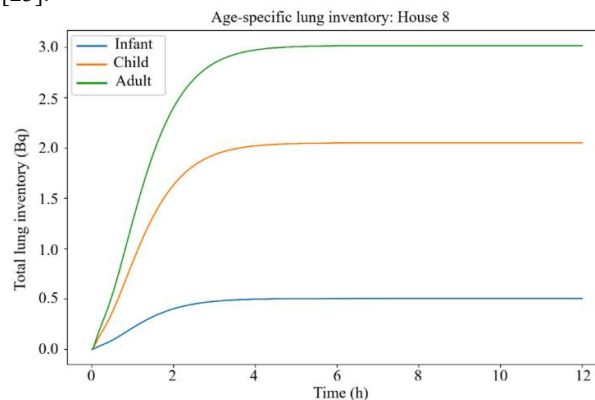


Fig. 3. Radon progeny inventories in infants, children, and adults for House 8 (54.23 Bq m^{-3}), which has the highest concentration of radon measured.

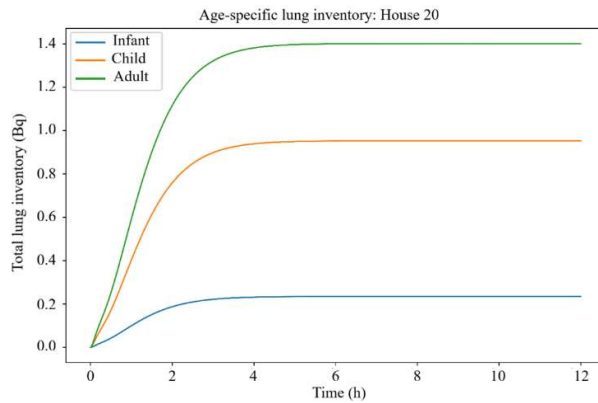


Fig. 4. Radon progeny inventories in infants, children, and adults for House 20 (25.19 Bq m^{-3}), which has an intermediate concentration of radon measured.

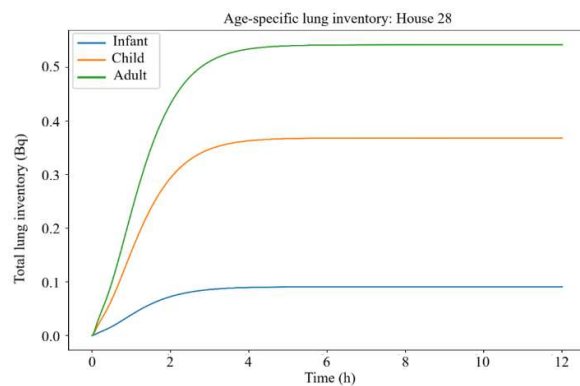


Fig. 5. Radon progeny inventories in infants, children, and adults for House 28 (9.74 Bq m^{-3}), which has the lowest concentration of radon measured.

D. The annual effective dose

The annual effective doses (Table X) have been determined by application of age-specific home-radon effective dose coefficients provided in ICRP Publication 158 [11]. The three exposure groups were associated with ICRP reference ages of 3 months, 10 years, and adult. The progeny-only coefficients used were 7.20×10^{-6} , 9.54×10^{-6} , and $9.32 \times 10^{-6} \text{ mSv per Bq h m}^{-3}$ for the 3 months, 10 years, and adult ages, respectively.

The calculated progeny-only annual effective doses are in the range of $0.563 - 3.135 \text{ mSv y}^{-1}$ for infants, $0.441 - 2.455 \text{ mSv y}^{-1}$ for children, and $0.431 - 2.398 \text{ mSv y}^{-1}$ for adults. For each age category, the mean values are 1.060, 0.830, and 0.811 mSv y^{-1} for infants, children, and adults, respectively.

Therefore, infants had the highest annual effective dose estimate, despite their lowest volumetric breathing rate in the present parameterisation. This increase in dose is mainly related to the use of the longer annual occupancy assumption (8030 h y^{-1}) together with the high age-specific ICRP 158 coefficient. The corresponding values of the coefficient-occupancy products are 0.057816, 0.045267, and 0.044223 mSv per Bq m^{-3} for infants, children, and adults, respectively.

Thus, the infant dose value is almost 31% higher compared to the adult value under the assumed exposure conditions.

For gas-plus-progeny sensitivity estimation, the mean values of annual doses are approximately 1.075, 0.844, and 0.826 mSv y^{-1} for infants, children, and adults, respectively. The insignificant difference with the progeny-only values shows that the contribution of the progeny dose dominates under the chosen home-radon reference conditions [11].

Finally, for House 8 (high-concentration dwelling), the progeny-only annual doses are 3.135 mSv y^{-1} for infants, 2.455 mSv y^{-1} for children, and 2.398 mSv y^{-1} for adults.

1) Worked Example for House 8

House 8 had the highest verified indoor radon concentration, $C = 54.23 \text{ Bq m}^{-3}$. For the infant (3 months) reference age, the annual occupancy time was 8030 h y^{-1} , and the ICRP 158 progeny-only home-radon coefficient was $7.20 \times 10^{-6} \text{ mSv per Bq h m}^{-3}$.

Therefore:

$$H_E = (54.23 \text{ Bq m}^{-3})(8030 \text{ h y}^{-1})(7.20 \times 10^{-6} \text{ mSv per Bq h m}^{-3})$$

$$H_E = 3.135 \text{ mSv y}^{-1}$$

For the child (10 years) reference age, the annual occupancy time was 4745 h y^{-1} , and the ICRP 158 progeny-only home-radon coefficient was $9.54 \times 10^{-6} \text{ mSv per Bq h m}^{-3}$.

$$H_E = (54.23 \text{ Bq m}^{-3})(4745 \text{ h y}^{-1})(9.54 \times 10^{-6} \text{ mSv per Bq h m}^{-3})$$

$$H_E = 2.455 \text{ mSv y}^{-1}$$

For the adult reference age, the annual occupancy time was 4745 h y^{-1} , and the ICRP 158 progeny-only home-radon coefficient was $9.32 \times 10^{-6} \text{ mSv per Bq h m}^{-3}$.

$$H_E = (54.23 \text{ Bq m}^{-3})(4745 \text{ h y}^{-1})(9.32 \times 10^{-6} \text{ mSv per Bq h m}^{-3})$$

$$H_E = 2.398 \text{ mSv y}^{-1}$$

E. Limitations

Since the sampling technique used was stratified purposive sampling, the thirty selected houses were meant to be representative of the housing categories and not through probability sampling. Consequently, the concentration results, comparisons across housing categories, lung burdens, and annual dose calculations need to be considered as the results for the houses sampled and not applied generally to all other residential structures in Murang'a County. A more comprehensive probability sampling study covering other areas and seasons is needed to develop county-wide estimates.

Consequently, this study includes the 8-hour measurement period and the relatively small sample size, involving only 30 houses, which do not allow for seasonal and long-term variations of indoor radon concentrations. Therefore, annual dose estimates assume that the measured concentration represents the annual period of exposure, as defined by annual occupancy periods. [2–3], [24].

Another limitation related to the modelling is the set of assumptions and uncertainties associated with the ICRP HRTM, including age-specific physiological parameters,

deposition fractions depending on aerosol size, mechanical clearance, absorption and transfer rates between compartments. These parameters might be different for different people and hence affect the estimated lung inventories and doses. [11], [13], [23–24].

Moreover, the assumptions of occupancy periods and reference-age physiological parameters reflect exposure

scenarios but not real-life data and hence make the annual effective doses modelled ones, depending on those assumptions and on the applicability of the selected ICRP Publication 158 dose coefficients. Hence, the calculated doses should be interpreted as modelled estimates of radiological exposure rather than individual doses and effects of health outcomes.

Table X. Age-specific annual effective doses resulting from indoor radon exposure in residential houses with varying radon concentrations.

House	Radon Concentration ($Bq\ m^{-3}$)	Infant Dose $mSv\ y^{-1}$	Child Dose $mSv\ y^{-1}$	Adult Dose $mSv\ y^{-1}$
House 1	38.36	2.218	1.736	1.696
House 2	17.62	1.019	0.798	0.779
House 3	11.64	0.673	0.527	0.515
House 4	13.43	0.776	0.608	0.594
House 5	19.93	1.152	0.902	0.881
House 6	12.84	0.742	0.581	0.568
House 7	11.61	0.671	0.526	0.513
House 8	54.23	3.135	2.455	2.398
House 9	11.21	0.648	0.507	0.496
House 10	12.05	0.697	0.545	0.533
House 11	13.89	0.803	0.629	0.614
House 12	17.82	1.030	0.807	0.788
House 13	17.80	1.029	0.806	0.787
House 14	13.69	0.792	0.620	0.605
House 15	13.28	0.768	0.601	0.587
House 16	16.41	0.949	0.743	0.726
House 17	12.66	0.732	0.573	0.560
House 18	13.32	0.770	0.603	0.589
House 19	10.97	0.634	0.497	0.485
House 20	25.19	1.456	1.140	1.114
House 21	18.11	1.047	0.820	0.801
House 22	12.17	0.704	0.551	0.538
House 23	30.47	1.762	1.379	1.347
House 24	49.55	2.865	2.243	2.191
House 25	15.24	0.881	0.690	0.674
House 26	15.30	0.885	0.693	0.677
House 27	16.33	0.944	0.739	0.722
House 28	9.74	0.563	0.441	0.431
House 29	12.51	0.723	0.566	0.553
House 30	12.55	0.726	0.568	0.555

IV. CONCLUSION

This study highlights the potential utility of incorporating indoor radon measurements and age-dependent ICRP HRTM modelling in the assessment of respiratory exposure in Murang'a County. The study has shown that lung inventories and effective doses differ because they are influenced by age-specific physiological and dosimetric factors.

Modelling provided a reproducible tool for relating measured radon concentrations and their progeny to their deposition and retention in the lungs. However, the calculated doses rely on the 8-h measurements, annual occupancy, aerosol and deposition parameters, and uncertainties associated with HRTM modelling. Hence, they should be

considered radiological exposure estimates based on the model rather than evidence of adverse health effects.

Overall, this study provides a valuable basis for further work on long-term radon monitoring and age-dependent radiological exposure assessment in Kenya.

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