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Measurement of Radon Gas Released from Human Blood Samples in Najaf and Karbala Governorates, Iraq

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ABSTRACT: *Background and Objectives: Radon (^{222}Rn) is a naturally occurring radioactive noble gas and a recognized carcinogen associated primarily with lung cancer. Data regarding radon released from human blood samples remain limited, particularly in Iraq. This study aimed to estimate radon activity measured in the equilibrated headspace above blood samples collected from healthy volunteers and patients in Najaf and Karbala governorates and to evaluate variations according to sex and smoking status. Materials and Methods: Thirty venous blood samples were collected from Al-Sadr Teaching Hospital in Najaf and Al-Husseini Hospital in Karbala between June and September 2023. Samples were transferred in EDTA tubes at 4 °C to the Physics Laboratory, Faculty of Science, University of Kufa. Radon activity released into the sealed headspace above blood samples was measured using a calibrated Canary Airthings digital radon monitor over a continuous monitoring period. Measured values were recorded in pCi/L and converted to Bq/m³ using the standard conversion factor. Results: Measured radon concentrations ranged from 0.090 pCi/L (3.33 Bq/m³) to 0.623 pCi/L (23.05 Bq/m³). Smokers exhibited higher mean concentrations than non-smokers, while males showed slightly higher values than females. All recorded concentrations were substantially below internationally recognized indoor radon reference levels. Conclusions: Radon concentrations released from the studied blood samples were low in all participants. Slightly elevated values observed among smokers and some occupationally exposed individuals suggest the importance of continued environmental radon monitoring. The study provides preliminary baseline data for future investigations of radon exposure in Iraqi populations.*

Keywords: *Radon; Blood samples; Airthings Canary; Radioactivity; WHO guidelines; Iraq; Lung cancer risk; Environmental radiation*

1. INTRODUCTION

Radon (^{222}Rn, atomic number 86) is a colorless, odorless, and chemically inert radioactive noble gas that forms naturally as an intermediate decay product in the uranium-238 (^{238}U) and thorium-232 (^{232}Th) decay chains, both of which are ubiquitous in the Earth's crust [1,2]. As a direct daughter of radium-226 (^{226}Ra), radon is continuously produced wherever uranium and radium are present in soils, rocks, and building materials. The most radiologically relevant isotope, ^{222}Rn, has a half-life of 3.82 days, making it sufficiently long-lived to migrate from soil and rocks into indoor environments before further decay [3]. Epidemiological evidence consistently identifies radon as the second most important cause of lung cancer after cigarette smoking, accounting for an estimated 3–14% of all lung cancer deaths worldwide and for the majority of lung cancer cases among non-smokers [4,5]. The primary hazard does not arise from radon itself, which is an inert gas readily exhaled, but from its short-lived progeny—principally polonium-218 (^{218}Po) and polonium-214 (^{214}Po)—which emit alpha particles capable of delivering ionizing radiation directly to bronchial epithelial cells, thereby initiating carcinogenesis through DNA strand breaks [6]. Human exposure to radon occurs predominantly through inhalation in enclosed or poorly ventilated spaces such as residential basements and ground-floor rooms, but also through ingestion of radon-contaminated water and food. Once absorbed, radon and its progeny are transported via the bloodstream throughout the body, where radioactive daughters deposit preferentially in mineralized tissues such as bone and joints [7]. The dose delivered to lung tissue by inhaled radon progeny is estimated to be two to three times greater than that received by the gastrointestinal tract through ingestion, owing to the short range of alpha particles in tissue [8]. Although WHO and EPA reference levels were established for residential indoor air exposure over long periods and are not directly applicable to headspace radon measurements above blood samples, they are provided in this study strictly for general context. They should not be interpreted as biological safety thresholds for blood-derived measurements [9]. The US Environmental Protection Agency (EPA) advises remediation of residential spaces exceeding 4.0 pCi/L (148 Bq/m³) [10]. Several European regulatory bodies, including those of the United Kingdom (200 Bq/m³) and Germany (250 Bq/m³), have established higher national thresholds, though these do not imply safe exposure below the limit, as any level of ionizing radiation carries some carcinogenic risk.

Despite the recognized health implications of radon exposure, quantitative data on radon concentrations in human blood remain extremely scarce, particularly in Middle Eastern populations. Iraq's geology—characterized by uranium-rich sedimentary and phosphate-bearing formations—creates conditions favorable for elevated environmental radon. Yet, to our knowledge, no previous study has directly radon activity measured in the equilibrated headspace above blood samples from the Najaf or Karbala regions. This study was therefore undertaken to: (i) quantify radon concentrations in human blood using a portable digital radon

monitor; (ii) compare concentrations between males and females; (iii) assess the influence of tobacco smoking; and (iv) evaluate whether observed values comply with WHO and EPA reference levels.

2. MATERIALS AND METHODS

2.1 Study Area and Ethical Considerations

Blood samples were collected from volunteers residing in two Iraqi governorates: Najaf and Karbala. Najaf is a central Iraqi province characterized by an arid climate and limestone-dominant geology. Karbala, located approximately 80 km to the northeast, shares similar geological features. Both cities contain significant urban and semi-industrial zones and host major teaching hospitals. Written informed consent was obtained from all participants. Sample collection followed the protocols established by the University of Kufa Faculty of Science Ethics Committee. No personal identifying information was linked to analytical results. In the laboratory, each blood sample was placed inside a sealed airtight measurement chamber and allowed to equilibrate for approximately 30 min at room temperature (20–22 °C). Radon released from the blood sample into the chamber headspace was subsequently monitored using the radon detector. Therefore, the measured values represent radon activity in the equilibrated air phase above the blood samples rather than direct dissolved-radon quantification within blood itself. EDTA tubes were selected because they are routinely used for blood preservation and minimize clot formation during transport. However, EDTA may alter erythrocyte membrane properties and potentially influence gas release kinetics.

2.2 Sample Collection and Preparation

A total of 30 venous blood samples were collected between June and September 2023: 15 from clinically healthy volunteers (control group) 15 from patients diagnosed with various medical conditions (patient group). Due to the heterogeneous nature of these conditions, specific diagnoses were not stratified in the final analysis, which constitutes a limitation of this preliminary study. Healthy control samples were obtained from volunteers presenting at Al-Husseini Hospital, Karbala, while patient samples were drawn at Al-Sadr Teaching Hospital, Najaf. Samples from both sexes and a wide age range (23–56 years) were included. Participant demographics, including sex, age, location, health status, and smoking behavior, are summarized in Table 1. All samples were collected using standard evacuated tubes containing ethylenediaminetetraacetic acid (EDTA) as an anticoagulant (BD Vacutainer® K2EDTA). Tubes were immediately transferred to insulated cold boxes maintained at 4 °C to preserve sample integrity and prevent clotting prior to analysis. Samples were transported to the Physics Laboratory, Faculty of Science, University of Kufa, within four hours of collection. In the laboratory, each blood sample was placed inside a dedicated airtight measurement container. The container was sealed and pre-equilibrated for 30 minutes at room temperature (20–22 °C) to allow radon outgassing from the liquid matrix into the headspace before inserting the sensor.

2.3 Measurement Device and Protocol

Radon measurements were performed using a Canary Airthings digital portable radon monitor (Airthings AS, Oslo, Norway), which operates using alpha-particle detection with a silicon photodiode sensor. The instrument is primarily designed for indoor air radon monitoring. In this study, it was used experimentally to estimate radon released into the sealed headspace above blood samples. Measurements should therefore be interpreted as preliminary screening estimates rather than absolute biological radon concentrations.

2.4 Unit Conversion and Data Analysis

Measured values in pCi/L were converted to Bq/m³ using the standard conversion factor: 1 pCi/L = 37 Bq/m³. Descriptive statistics (mean, minimum, maximum) were computed for all sub-groups. Comparisons between males and females, and between smokers and non-smokers, were performed using independent-samples t-tests with a significance threshold of $p < 0.05$. All analyses were conducted in Microsoft Excel 365.

3. RESULTS

3.1 Subject Demographics

The study enrolled 30 participants: 17 males and 13 females, with a mean age of 30.4 ± 7.6 years (range 23–56 years). Of these, 10 were active smokers and 20 were non-smokers. Table 1 presents the complete demographic profile of all participants. Hematological parameters such as hemoglobin concentration and hematocrit were not available and therefore could not be evaluated as potential determinants of radon release kinetics.

Table 1. Demographic characteristics of study participants (n = 30).

No.	Sex	Age	Location	Health Status	Smoking	Occupation	Group
1	Male	27	Karbala	Healthy	Smoking	Hospital worker	Patient group
2	Male	25	Karbala	Healthy	Smoking	Hospital worker	Patient group
3	Male	28	Karbala	Healthy	Smoking	Hospital worker	Patient group
4	Male	29	Karbala	Healthy	Smoking	Hospital worker	Patient group
5	Male	26	Karbala	Healthy	Smoking	Hospital worker	Patient group
6	Male	24	Karbala	Healthy	Non-smoking	General	Control group
7	Male	25	Karbala	Patient	Non-smoking	General	Patient group
8	Female	24	Karbala	Healthy	Non-smoking	General	Control group
9	Female	30	Karbala	Healthy	Non-smoking	General	Control group
10	Female	35	Najaf	Patient	Non-smoking	Hospital	Patient group
11	Female	56	Najaf	Patient	Non-smoking	Hospital	Patient group
12	Female	37	Najaf	Patient	Non-smoking	Hospital	Patient group
13	Male	35	Najaf	Patient	Non-smoking	Hospital	Patient group
14	Female	35	Najaf	Patient	Non-smoking	Hospital	Patient group
15	Female	40	Karbala	Healthy	Non-smoking	General	Control group
16	Female	30	Karbala	Healthy	Non-smoking	General	Control group
17	Female	23	Najaf	Patient	Non-smoking	Hospital	Patient group
18	Male	34	Najaf	Patient	Non-smoking	General	Patient group
19	Male	23	Najaf	Patient	Smoking	General	Patient group
20	Female	25	Karbala	Healthy	Non-smoking	General	Control group
21	Male	23	Najaf	Patient	Non-smoking	Hospital	Patient group
22	Female	34	Najaf	Patient	Non-smoking	Hospital	Patient group
23	Female	23	Najaf	Patient	Non-smoking	General	Patient group
24	Male	41	Najaf	Patient	Non-smoking	Hospital	Patient group
25	Male	25	Najaf	Patient	Non-smoking	General	Patient group
26	Female	30	Karbala	Healthy	Non-smoking	General	Control group
27	Female	28	Karbala	Healthy	Non-smoking	General	Control group
28	Male	30	Najaf	Patient	Smoking	Hospital	Patient group
29	Female	26	Karbala	Healthy	Non-smoking	General	Control group

* Detailed smoking history was not collected.

3.2 Radon Concentrations in Healthy Subjects

Table 2 presents the daily short-term and long-term radon readings, along with mean values, for the 15 healthy subjects measured over a two-day period. Short-term mean concentrations ranged from 0.090 pCi/L (3.33 Bq/m³) in sample BS-H1 to 0.415 pCi/L (15.36 Bq/m³) in sample BS-H12. Long-term means followed a similar distribution, spanning from 0.105 pCi/L to 0.530 pCi/L.

Table 2. Short-term and long-term radon (pCi/L) from healthy subjects

Sample ID	Sex	Smoking	Short-term Day 1 (pCi/L)	Short-term Day 2 (pCi/L)	Short-term Mean (pCi/L)	Long-term Day 1 (pCi/L)	Long-term Day 2 (pCi/L)	Long-term Mean (pCi/L)
BS-H1	Male	Non-smoking	0.02	0.16	0.09	0.08	0.13	0.105
BS-H2	Female	Non-smoking	0.02	0.21	0.115	0.24	0.21	0.225
BS-H3	Male	Non-smoking	0.02	0.37	0.195	0.08	0.18	0.130
BS-H4	Male	Non-smoking	0.27	0.24	0.255	0.24	0.24	0.240
BS-H5	Male	Smoking	0.19	0.20	0.195	0.18	0.20	0.190
BS-H6	Male	Non-smoking	0.23	0.28	0.255	0.22	0.25	0.235
BS-H7	Male	Smoking	0.30	0.32	0.310	0.25	0.28	0.530
BS-H8	Male	Non-smoking	0.40	0.42	0.410	0.38	0.40	0.390
BS-H9	Female	Non-smoking	0.28	0.30	0.290	0.25	0.26	0.255
BS-H10	Female	Non-smoking	0.32	0.33	0.325	0.30	0.32	0.310
BS-H11	Female	Non-smoking	0.35	0.33	0.340	0.40	0.42	0.410
BS-H12	Female	Non-smoking	0.40	0.43	0.415	0.40	0.44	0.420
BS-H13	Female	Non-smoking	0.40	0.42	0.410	0.38	0.40	0.390
BS-H14	Female	Non-smoking	0.22	0.25	0.235	0.20	0.25	0.225
BS-H15	Female	Non-smoking	0.28	0.35	0.315	0.28	0.33	0.305

3.3 Radon Concentrations in Patient Subjects

Table 3 shows the four-day daily measurements for the 15 patient samples, separately for males (BS-P1 through BS-P8) and females (BS-F1 through BS-F7). The highest single daily short-term reading was 1.05 pCi/L (38.85 Bq/m³), recorded in sample

BS-P2 on Day 3, which was attributed to a male smoker with an occupational history involving hospital work. Mean short-term concentrations across all patient samples ranged from 0.115 pCi/L to 0.583 pCi/L. In all cases, mean concentrations remained below the WHO intervention level of 2.7 pCi/L (100 Bq/m³) and far below the EPA action level. For contextual environmental comparison only, the measured headspace activities were numerically lower than commonly cited indoor air radon reference levels established for residential environments. These environmental benchmarks are not directly applicable to biological headspace measurements.

Table 3. Radon (pCi/L) from patient subjects over four measurement days.

Sample ID	Sex	Short Day 1 (pCi/L)	Short Day 2 (pCi/L)	Short Day 3 (pCi/L)	Short Day 4 (pCi/L)	Short Mean (pCi/L)	Long Mean (pCi/L)	Overall Mean (pCi/L)
BS-P1	Male	0.62	0.37	0.72	0.62	0.583	0.54	0.54
BS-P2	Male	0.02	0.45	1.05	0.70	0.555	0.64	0.54
BS-P3	Male	0.37	0.27	0.13	0.32	0.273	0.37	0.29
BS-P4	Male	0.02	0.21	0.08	0.24	0.138	0.18	0.21
BS-P5	Male	0.02	0.24	0.29	0.27	0.205	0.24	0.24
BS-P6	Male	0.13	0.18	0.10	0.05	0.115	0.16	0.16
BS-P7	Male	0.18	0.51	0.24	0.37	0.325	0.13	0.24
BS-P8	Male	0.02	0.21	0.13	0.18	0.135	0.35	0.35
BS-F1	Female	0.45	0.32	0.33	0.35	0.363	0.28	0.45
BS-F2	Female	0.20	0.28	0.22	0.22	0.230	0.20	0.25
BS-F3	Female	0.58	0.38	0.40	0.42	0.445	0.54	0.38
BS-F4	Female	0.20	0.30	0.25	0.20	0.238	0.20	0.22
BS-F5	Female	0.18	0.22	0.30	0.32	0.255	0.20	0.22
BS-F6	Female	0.18	0.20	0.22	0.25	0.213	0.18	0.16
BS-F7	Female	0.35	0.40	0.28	0.30	0.333	0.35	0.35

3.4 Comparative Summary Statistics

Table 4 provides a consolidated comparison of radon concentrations across key demographic and clinical sub-groups. Males demonstrated a higher grand mean radon concentration (0.299 pCi/L; 11.1 Bq/m³) compared to females (0.279 pCi/L; 10.3 Bq/m³). Smokers showed a substantially elevated grand mean (0.354 pCi/L; 13.1 Bq/m³) relative to non-smokers (0.262 pCi/L; 9.7 Bq/m³). The overall grand mean across all 30 samples was 0.298 pCi/L (11.0 Bq/m³), corresponding to 11.0% of the WHO guideline level and 7.5% of the EPA action level. The mean radon activity measured in the equilibrated headspace above blood samples was higher among smokers compared with non-smokers, although the difference did not reach statistical significance (mean difference = 0.066 pCi/L, 95% CI: −0.163 to 0.295; t(13)=0.63, p=0.540, Cohen's d = 0.49).

Table 4. Summary of radon concentration statistics by sub-group, with WHO and EPA compliance status.

Group	Max (pCi/L / Bq/m3)	Min Mean (pCi/L / Bq/m3)	Grand Mean (pCi/L / Bq/m3)	WHO Status (100 Bq/m3)	EPA Status (148 Bq/m3)
Males (all)	0.605 / 22.4	0.090 / 3.3	0.299 / 11.1	Below WHO	Below EPA
Females (all)	0.445 / 16.5	0.115 / 4.3	0.279 / 10.3	Below WHO	Below EPA
Smokers	0.610 / 22.6	0.115 / 4.3	0.354 / 13.1	Below WHO	Below EPA
Non-smokers	0.445 / 16.5	0.090 / 3.3	0.262 / 9.7	Below WHO	Below EPA
Patient group	0.623 / 23.1	0.135 / 5.0	0.315 / 11.7	Below WHO	Below EPA
Control group	0.445 / 16.5	0.090 / 3.3	0.270 / 10.0	Below WHO	Below EPA

Group	Max (pCi/L / Bq/m3)	Min Mean (pCi/L / Bq/m3)	Grand Mean (pCi/L / Bq/m3)	WHO Status (100 Bq/m3)	EPA Status (148 Bq/m3)
Overall (n=30)	0.623 / 23.1	0.090 / 3.3	0.298 / 11.0	Below WHO	Below EPA

3.5 Unit Conversion Reference

Table 5 cross-references key measured values with their Bq/m³ equivalents and places them in context relative to internationally recognized intervention thresholds. In all cases, observed radon concentrations were at least an order of magnitude below actionable levels. The mean radon activity measured in the equilibrated headspace above blood samples did not differ significantly between males and females (mean difference = −0.032 pCi/L, 95% CI: −0.124 to 0.060; t(28)=−0.72, p=0.479, Cohen's d = −0.26).

Table 5. Conversion of representative measured concentrations from pCi/L to Bq/m³ and comparison with international guidelines.

Measured Value (pCi/L)	Converted Value (Bq/m³)	Guideline Threshold	Compliance
0.090	3.33	WHO guideline: 100 Bq/m³	**Below**
0.195	7.22	WHO guideline: 100 Bq/m³	**Below**
0.298	11.03	WHO guideline: 100 Bq/m³	**Below**
0.605	22.39	US EPA action: 148 Bq/m³ (4.0 pCi/L)	**Below**
0.623	23.05	US EPA action: 148 Bq/m³ (4.0 pCi/L)	**Below**
4.0 (EPA)	148	US EPA intervention level	**Reference**
2.7 (WHO)	100	WHO intervention level	**Reference**

3.6 Statistical Analysis

Data are presented as mean ± standard deviation (SD). Independent-samples t-tests were used to compare radon concentrations between males and females and between smokers and non-smokers. Statistical significance was defined at $p < 0.05$. Owing to the relatively small sample size, the statistical findings should be interpreted cautiously.

4. DISCUSSION

The primary finding of this study is that radon activity measured in the equilibrated headspace above blood samples from residents of Najaf and Karbala are well within WHO and EPA permissible limits, with a grand mean of approximately 11 Bq/m³—roughly one-tenth of the WHO reference level. This is consistent with findings from comparable studies conducted in Jordan, Egypt, and Saudi Arabia, where blood radon values in healthy populations typically range from 5 to 35 Bq/m³ [11,12]. The slightly higher radon concentrations observed in male participants (mean 11.1 Bq/m³ vs. 10.3 Bq/m³ for females) are in line with patterns reported in the literature and are most plausibly explained by differential occupational exposure. Among male participants, several were employed in hospital settings or construction sites, both of which represent environments with potentially elevated radon levels from building materials and inadequate ventilation [13]. In contrast, the majority of female participants in this cohort reported spending the greater portion of their time in domestic environments with more regular air exchange. Although the observed inter-sex difference was not statistically significant ($p = 0.38$), it is consistent in direction with findings from epidemiological studies in uranium-bearing geological regions [14].

The association between smoking and elevated blood radon concentrations, with smokers recording a mean approximately 35% higher than non-smokers in this cohort, warrants attention. Radon and tobacco smoke are recognized as synergistic lung carcinogens, with the combined risk of lung cancer in smokers who are simultaneously exposed to radon estimated to be far greater than the risk attributable to either factor alone [4,15]. From a mechanistic standpoint, the higher radon concentrations in smokers observed here may reflect a combination of factors: (i) increased respiratory depth and frequency in habitual smokers, increasing radon uptake per unit time; (ii) damage to mucociliary clearance mechanisms in the bronchial airways by tobacco smoke, prolonging residence time of radon progeny; and (iii) potential co-absorption through contaminated indoor air in smoking environments [16]. No statistically significant difference was found between radon concentrations in the patient and control groups ($p = 0.51$), suggesting that the medical conditions present in the patient group did not substantially alter radon uptake or distribution in blood at the exposure

levels encountered. This finding aligns with the expectation that at low environmental radon concentrations, blood radon levels primarily reflect ambient exposure rather than pathophysiological differences in uptake. The highest single radon reading recorded in this study—1.05 pCi/L (38.85 Bq/m³) from a male smoker employed in a hospital—while still well below actionable thresholds, highlights the potential for concentration hot spots among occupationally exposed individuals. This underscores the value of routine radon monitoring in healthcare facility workers, a recommendation echoed by the International Commission on Radiological Protection (ICRP) [17]. Several limitations should be noted. First, sample size was modest (n = 30), limiting statistical power for sub-group comparisons. Second, although the Canary Airthings device is factory-calibrated and widely used in research settings, its design for indoor air measurement, rather than blood headspace analysis, introduces a potential source of systematic measurement error. Third, the study did not include measurements of residential indoor radon concentrations for participants, precluding direct correlation between environmental and blood radon levels. Future studies should incorporate parallel indoor radon measurements and recruit larger, stratified cohorts to permit multivariable regression analysis. Several methodological limitations should be considered. The detector employed in this study was originally developed for indoor air monitoring rather than biological specimen analysis. Consequently, the reported values represent radon activity measured in the sealed air headspace above blood samples and not direct dissolved-radon concentrations. In addition, the relatively small sample size and absence of parallel indoor radon measurements limited the ability to establish detailed exposure correlations. Because EDTA is a calcium-chelating anticoagulant, alterations in erythrocyte membrane integrity and permeability may have influenced radon release into the headspace. Therefore, the measured values should be interpreted specifically as radon activity released from EDTA-anticoagulated blood samples rather than direct in vivo dissolved-radon concentrations. Future studies should compare EDTA and heparinized samples. Samples were stored at 4 °C and subsequently equilibrated at room temperature prior to measurement. This temperature transition may have enhanced passive radon outgassing from blood into the sealed headspace, potentially leading to overestimation of physiologic in vivo radon activity. The magnitude of this effect was not quantified and should be investigated in future validation studies.

5. CONCLUSIONS

This exploratory study demonstrated low radon activity levels in the sealed headspace above blood samples collected from participants in Najaf and Karbala governorates. All measured values were substantially below internationally recognized indoor radon reference levels. Slightly higher concentrations were observed among smokers and some occupationally exposed participants. Future investigations using validated biological radon assessment techniques and larger study populations are recommended to confirm these findings and better characterize radon exposure pathways in Iraq. Although the 4-hour transport interval represents minimal radioactive decay relative to the 3.82-day half-life of radon-222, passive radon loss during storage and handling cannot be excluded. Stability experiments were not performed and should be included in future studies.

Author Contributions

A.H.R.: sample collection, field measurements, data compilation, and initial manuscript drafting. B.A.A.: conceptualization, methodology, laboratory supervision, data analysis, manuscript review and editing, and corresponding author responsibilities. Both authors have read and approved the final manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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