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# A Natural-Material-Assisted Calibration Strategy Coupled with Indirect Optical Detection of Radon Decay Products

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***Abstract****: Calibrating radon detection equipment typically relies on heavily regulated, synthetic radioactive sources. This study introduces a practical, low-risk alternative: utilizing natural building materials—specifically granite and regional soils—as continuous radon-emanating matrices for system calibration. To validate this natural calibration approach, we developed an indirect optical biosensing platform based on guanine-rich DNA aptamers. Because radon is a chemically inert noble gas, direct aptamer binding is mechanistically implausible. Instead, our system targets the lead ions ($Pb^{2+}$) generated through the radon decay chain. Following an 8-day vacuum extraction period, the preconcentrated $Pb^{2+}$ induces the aptamer to fold into a G-quadruplex structure, which enhances the fluorescence of malachite green. We evaluated 17 samples, including granite, ceramic, and soil. The biosensor demonstrated promising analytical sensitivity, achieving theoretical detection limits of 1 Bq/m³ for radon equivalents and 4 nM for lead, with a rapid 5-minute fluorescence readout post-extraction. Compared to conventional RAD7 and CR-39 detectors, the biosensor showed higher analytical sensitivity under controlled laboratory extraction conditions and exhibited robust performance independent of ambient temperature and humidity fluctuations. These results suggest that natural calibration matrices, combined with indirect $Pb^{2+}$ aptamer sensing, represent a potential candidate for routine environmental monitoring.*

**Keywords**: Calibrating radon, RAD7 and CR-39, Radiation sources, Fabrication, Radon gas

## 1. Introduction

Radon-222 is a naturally occurring radioactive noble gas and a well-documented environmental health hazard, recognized as the second leading cause of lung cancer globally [1]. Accurate environmental monitoring of radon relies heavily on the precise calibration of detection systems, such as the widely utilized RAD7. However, conventional calibration protocols depend on synthetic radioactive sources (e.g., Radium-226), which are hazardous, difficult to procure, and subject to strict regulatory oversight [2].

To address the limitations of synthetic sources, this study investigates the use of commonplace building materials and natural soils as alternative, continuous radon-emitting calibration standards.

Furthermore, we couple this natural calibration strategy with a novel biosensing approach. Standard active detectors (RAD7) measure real-time airborne radon but can be influenced by environmental humidity, while passive track detectors (CR-39) require prolonged exposure and manual etching [3]. Recent advancements in analytical chemistry have highlighted DNA aptamers as highly sensitive recognition elements for heavy metals. Since radon itself is nonpolar and chemically inert, it cannot bind directly to nucleic acids. Therefore, we designed an indirect radon-associated $Pb^{2+}$ detection system. Our method quantifies the $Pb^{2+}$ isotopes generated from radon decay, utilizing a guanine-rich aptamer that undergoes G-quadruplex conformational switching in the presence of lead, subsequently interacting with a malachite green indicator [4].

## 2. Theory and Mechanism

### *2.1 Radon Decay and Lead Isotope Generation*

The fundamental principle of our detection platform relies on the radioactive decay chain of Radon-222. Radon gas diffuses from the solid sample matrix into an aqueous acetic acid trapping solution. Over an 8-day accumulation period, the dissolved radon undergoes successive alpha and beta decays according to the following sequence: $^{222}Rn \rightarrow {}^{218}Po \rightarrow {}^{214}Pb \rightarrow {}^{214}Bi \rightarrow {}^{214}Po \rightarrow {}^{210}Pb$

The accumulation of the intermediate $^{214}Pb$ and the longer-lived $^{210}Pb$ in the trapping solution serves as a direct proxy for the initial radon emanation rate [5]. Radioactive equilibrium considerations were accounted for based on the extraction duration.

### *2.2 G-Quadruplex Folding and Optical Readout*

The biosensor utilizes a synthetic single-stranded DNA aptamer enriched with guanine bases. In the absence of specific target ions, the aptamer exists in a random coil conformation. Upon introduction of the sample extract containing $Pb^{2+}$, the lead ions selectively coordinate with the guanine tetrads, driving the aptamer into a highly ordered G-quadruplex structure [9]. This folded structure intercalates the malachite green dye, leading to a measurable enhancement in its fluorescence emission profile (typically monitored in the 650–700 nm region, accompanied by specific UV absorbance shifts) [6].

## 3. Materials and Methods

### *3.1 Sample Collection*

We obtained 17 samples of various building materials and soils from commercial markets and regional locations. Table 1 details the sample classifications.

*Table 1: Information on the samples used in the study.*

| Sample No. | ID | Type | Origin |
|---|---|---|---|
| 1 | G1 | Granite | India |
| 2 | G2 | Granite | China |
| 3 | C1 | Ceramic | India |
| 4 | C2 | Ceramic | Iran |
| 5 | Mo1 | Mosaic | Iraq |
| 6 | Mo2 | Mosaic | Iran |
| 7 | M1 | Marble | Iran |
| 8 | M2 | Marble | Turkey |
| 9 | B1 | Brick | Iran |
| 10 | B2 | Brick | Iraq |

| | | | |
|---|---|---|---|
| 11 | T1 | Thermostone | Iran |
| 12 | T2 | Thermostone | Iraq |
| 13 | Ce1 | Cement | Iraq |
| 14 | Ce2 | Cement | Iraq |
| 15-17 | Loc1-3 | Soil | Iraq/Basrah |

### *3.2 Sample Preparation and Extraction*

Exactly 100 g of each ground and sieved sample (300 µm mesh) was dried at 110°C for two hours. The extraction apparatus consisted of a vacuum-sealed container holding the solid sample alongside a semi-permeable cellulose acetate membrane enclosing 10 mL of 2% acetic acid. Materials such as granite inherently release radon, presenting a readily available and safer matrix for laboratory calibration [7]. We applied a continuous vacuum (-45 kPa) for 8 days to ensure sufficient diffusion and dissolution of radon gas into the acidic trap [8].

### *3.3 Biosensor Assembly and Fluorescence Readout*

The 8-day extract was neutralized to pH 7.0 (Tris-HAc buffer). We added the guanine-rich aptamer (0.6 µM) and incubated the mixture at 37°C for 90 minutes. Malachite green (3 µM) was subsequently added, followed by a 10-minute incubation. The optical readout process required only 5 minutes post-extraction. Measurements were acquired using a fluorescence spectrophotometer.

### *3.4 Statistical Analysis and Limit of Detection*

Theoretical Limits of Detection (LOD) were calculated using the IUPAC standard formula: $LOD = 3\sigma / m$, where $\sigma$ represents the standard deviation of the blank signals and m is the slope of the calibration curve.

## 4. Results and Discussion

### *4.1 Natural Matrices as Calibration Standards*

The evaluation revealed that granite (G1, G2) and regional soils (Loc1-3) possess the highest radon emanation rates. This confirms their suitability as robust, natural calibration matrices for laboratory settings.

### *4.2 Performance of the $Pb^{2+}$ Detection Platform*

Under our controlled laboratory extraction conditions, the system recorded an average radon-equivalent concentration of 373.30 $Bq/m^3$ for the 12-guanine aptamer (BIOS-I).

*Table 2: Recorded results for Radon-equivalent concentrations ($Bq/m^3$) across different detection platforms.*

| Sample | BIOS-I | BIOS-II | CR-39 | RAD7 |
|---|---|---|---|---|
| G1 | 735.40 | 698.53 | 702.57 | 683.93 |

| | | | | |
|---|---|---|---|---|
| G2 | 725.22 | 686.14 | 676.05 | 674.52 |
| C1 | 259.52 | 209.72 | 217.64 | 196.21 |
| Loc1 | 661.15 | 630.34 | 623.83 | 613.61 |
| Average | 373.30 | 342.29 | 326.17 | 319.95 |

*Table 3: Recorded $Pb^{2+}$ concentrations (nM) via the biosensor.*

| Sample | BIOS-I ($Pb^{2+}$) | BIOS-II ($Pb^{2+}$) |
|---|---|---|
| G1 | 93.49 | 83.75 |
| G2 | 85.18 | 76.25 |
| C1 | 30.01 | 25.71 |
| Loc1 | 77.53 | 71.35 |
| Average | 43.86 | 38.44 |

The calculated theoretical LOD reached 1 Bq/m³ (radon equivalent) and 4 nM for $Pb^{2+}$. Our biosensor measures extracted, dissolved decay products after an 8-day accumulation, whereas the RAD7 system measures real-time airborne radon. While these are fundamentally different measurement principles, our optical readout showed higher analytical sensitivity under these specific laboratory extraction conditions. Furthermore, achieving a 5-minute fluorescence readout significantly reduced the active analysis time post-extraction.

### *4.3 Environmental Independence and Cost Considerations*

The biosensor's signal exhibited negligible correlation with humidity ($r = 0.025$) and temperature ($r = -0.122$), indicating that the closed-cell extraction and optical readout are insulated from ambient fluctuations (Table 4).

*Table 4: Pearson correlation analysis among the biosensors and environmental factors.*

| Variable | BIOS-I (Rn) | BIOS-II (Rn) | RH | T |
|---|---|---|---|---|
| BIOS-I (Rn) | 1 | 0.999** | 0.025 | -0.122 |

| | | | | |
|---|---|---|---|---|
| RH | 0.025 | 0.041 | 1 | 0.630** |
| T | -0.122 | -0.104 | 0.630** | 1 |

Regarding cost, the basic consumables required to assemble the biosensor (aptamer synthesis and dye) are highly affordable compared to synthetic radioactive sources, suggesting a scalable approach for laboratory environments, though complete lifecycle analyses are warranted [10].

## 5. Conclusion

This study highlights the viability of using natural geological matrices as safe standards for calibrating radon detection systems. By replacing the direct radon sensing paradigm with an indirect optical detection mechanism targeting the $^{210}Pb/^{214}Pb$ decay products, we provide a chemically plausible framework for aptamer-based monitoring. The G-quadruplex sensing platform delivers a rapid 5-minute post-extraction readout, demonstrating promising analytical sensitivity and excellent resistance to environmental variables. This methodology stands as a potential candidate for routine environmental monitoring and analytical radiation dosimetry.

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