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Wire-mesh capped deposition sensors: Novel passive tool for coarse fraction flux estimation of radon thoron progeny in indoor environments

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ABSTRACT

Deposition-based ^{222}Rn and ^{220}Rn progeny sensors act as unique, passive tools for determining the long time-averaged progeny deposition fluxes in the environment. The use of these deposition sensors as progeny concentration monitors was demonstrated in typical indoor environments as conceptually superior alternatives to gas-based indirect monitoring methods. In the present work, the dependency of these deposition monitors on various environmental parameters is minimized by capping the deposition sensor with a suitable wire mesh. These wire-mesh capped deposition sensors measure the coarse fraction deposition flux, which is less dependent on the change in environmental parameters like ventilation rate and turbulence. The calibration of these wire-mesh capped coarse fraction progeny sensors was carried out by laboratory controlled experiments. These sensors were deployed both in indoor and in occupational environments having widely different ventilation rates. The obtained coarse fraction deposition velocities were fairly constant in these environments, which further confirmed that the signal on the wire-mesh capped sensors show the least dependency on the change in environmental parameters. This technique has the potential to serve as a passive particle sizer in the general context of nanoparticles using progeny species as surrogates. On the whole, there exists a strong case for developing a passive system that responds only to coarse fraction for providing alternative tools for dosimetry and environmental fine particle research.

1. Introduction

It is a fundamental knowledge that the inhalation doses due to radon (^{222}Rn) and thoron (^{220}Rn) are predominantly contributed by their progenies and not due to the gases themselves. Progeny measurements are being carried out essentially by either short-term active measurements like by air sampling on a substrate followed by alpha or beta counting (Tsivoglou et al., 1953; Kuznetz, 1956; Ruzer and Sextro, 1997; Solomon, 1997; Yu and Guan, 1998) or by continuous active monitoring techniques based on a silicon barrier detector (Furuta et al., 2000). However, due to the non-availability of satisfactory passive measurement techniques for the progeny species, it has been a usual practice to estimate the long time-averaged progeny concentration from measured gas concentration using an assumed equilibrium factor. The equilibrium factors, generally being estimated by one or few short-time air sampling techniques, are not expected to represent the entire long-term duration of passive gas measurements. To be accurate, one is required to measure the equilibrium factor *in situ*, along with the gas concentration. This being not practical, the assigned equilibrium factor (0.4 for indoor and 0.8 for outdoor for ^{222}Rn) approach has been an inevitable, though uncertain, part of the dosimetric strategies in both occupational and public domains.

For the case of thoron decay products, however, the equilibrium factor is of far more questionable validity, even as a concept in view of the far shorter half-life of the gas compared to its progeny, ^{212}Pb. Although these limitations have been known for a long time, the need for a shift from gas-based dosimetric paradigm to that based on the direct detection of progeny species cannot be overstated, considering the fundamental metrological principle to directly monitor the risk causing agents rather than their precursors.

While this is undoubtedly a daunting task in passive dosimetry, a promising approach seems to be the deposition sensing technique, which acts to serve as a cumulated deposition flux density meter of the progeny species. This idea was originally proposed by Zhuo et al. (2000) and has been systematically investigated by Mishra and Mayya (2008). It is attractive not only for its simplicity and diverse applicability as has been demonstrated by Mishra and Mayya (2008) but also because one can say with certainty that any signal obtained in a deposition sensor should necessarily be due to the deposited progeny atoms and there is absolutely no contribution from the gas. It is a point worth pondering whether this deposition flux could be a direct and superior index of radiological harm rather than either the progeny or the gas concentrations, in view of the fact that the deposition process on the detector surface roughly mimics the actual progeny deposition mechanism of the lung. This, however, is a

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complex question that needs to be examined by a detailed size-dependent study and statistical analysis of large number of scenarios. Pending such a demonstration, one has no option but to use air concentrations as measures of risk, at least in the context of radiological protection. While the air concentration estimated by the deposition sensor satisfies the requirement of direct progeny monitoring rigorously in a passive mode, its response coefficient (track density rate/unit concentration) hinges upon the concept of the "effective deposition velocity" for the progeny species. Through a large number of measurements in dwellings and in a test house, Mishra et al. (2009a,b) established that in general indoor environments, the effective deposition velocity remained fairly constant at about (0.075 ± 0.0072) m h^{-1} for the ^{220}Rn progeny and (0.132 ± 0.0036) m h^{-1} for the ^{222}Rn progeny. In contrast, careful measurements in a workplace in a thorium refinery showed consistently higher (by a factor 2 to 3) deposition velocities (Mishra et al., 2010). To understand the underlying factors responsible for these variations, deposition phenomena were carefully modeled by combining progeny attachment dynamics (Jacobi, 1972) with particle deposition models (Lai and Nazaroff, 2000). This showed that ~70% of the total deposition flux is contributed by the fine (unattached) fraction (~2 nm, ~2–4% for ^{212}Pb) and the remaining part by the coarse (attached) fraction (~150 nm) of the progeny atoms in the environment. The overall deposition velocity was found to depend mainly on three variables: a) ventilation rate, b) atmospheric turbulence, and c) coarse particle size distribution (Mishra et al., 2010). While the ventilation rate primarily affects the percentage of the fine fraction, air turbulence strongly affects its deposition velocity and both these factors have overwhelming influence on the effective deposition velocity. In comparison, their effect on coarse fraction deposition velocities is far less. In fact, the increased fine fraction of ^{212}Pb due to ventilation alone could largely explain the observed increase in the deposition velocity in the workplace environment, which was artificially maintained at a higher ventilation rate of about 4–6 air changes per hour. With regard to air turbulence, model calculations (Lai and Nazaroff, 2000) show that a 10-time increase in the friction velocity will result in a 10-time increase in the fine fraction deposition velocity, while the corresponding increase in the coarse fraction deposition velocity will be only about 4–5 times. This is because the coarse fraction laminar boundary layer thicknesses are far smaller, and in addition, gravitational sedimentation contributes to their deposition. Hence it may be reasoned that the deposition velocity of the coarse fraction, which carries an overwhelming part of the progeny activity concentration, will be insensitive to changes in the ventilation rates and relatively insensitive to changes in the air turbulence. Thus, one may visualize a relatively robust progeny deposition sensing technique if fine fraction can somehow be separated in a passive manner such that the sensor solely responds to the coarse fraction. This activity concentration can then be converted to potential alpha energy concentrations and lung doses using UNSCEAR formulae (2000). The response of such a sensor would still depend on the variability in particle size distribution, but one would have achieved an important progress by minimizing the effect of other two environmental dependencies. Once the mobile fine component is separated, it should be possible to estimate the characteristic particle size from within the sensing technique itself, for example, from differential orientation responses. It is not difficult to see that this technique has the potential to serve as a passive particle sizer in the general context of nanoparticles using progeny species as surrogates. On the whole, there exists a strong case for developing a passive system that responds only to a coarse fraction for providing alternative tools for dosimetry and environmental fine particle research.

It has been an established practice to employ a wire-mesh–filter-paper combination technique in flow mode for separating the fine and the coarse fractions to estimate the respective components of the progeny activities (Thomas and Hinchliffe, 1972; George; 1972; James et al., 1972). In this technique the air is sampled at an appropriate flow rate through the wire mesh such that a large part (>95%) of the fine fraction is captured by it while at the same time allowing a large part (>99%) of the coarse fraction to penetrate through the mesh for being collected on the filter paper. Despite a large body of theoretical development and practical applications, including recent resurgence of interest in this technique in the context of nanotechnology, there has been no attempt to use this technique in passive, turbulent or molecular diffusion modes. This is understandable if one views the wire mesh as a tool to estimate the fine fraction because in uncertain and undefined flow patterns that would be the rule in natural environments, a small increase in coarse fraction deposition on the wire mesh would overwhelm the activity component of the fine fraction deposited on it. On the other hand this uncertainty should pose no problem if one wishes to deploy the wire mesh merely as a fine fraction remover rather than as an estimator. To appreciate this, let us consider a natural environment in which the fine fraction (^{212}Pb for specificity) is about 3% and the air velocities fluctuate from 1–10 cm/s. Since the fine fraction deposition velocity on a surface is about 100 times higher than that for the coarse fraction, an overwhelming part (75%) of the deposited activity will be that due to the fine fraction (3% activity component). One can now devise a wire mesh having a penetration coefficient of about 1–5% for the fine fraction and 99–95% for the coarse fraction in this velocity range. In terms of the actual activities transmitted, one has 0.03–0.15% of the fine fraction and 96–94% of the coarse fraction. The deposited activity post wire mesh will have a contribution of 2.5–12% from the fine fraction and hence the fluctuation in the air velocity from 1 to 10 cm/s would have caused about 10% uncertainty in the activity deposited. Also, while the uncertainty in the activity collected on the wire mesh is large (500%) that in the transmitted activity is quite small (~5%). If one detects only the transmitted activity by optimizing the sensor location at an appropriate distance from the wire mesh, one would then achieve a reliable coarse fraction sensor. Thus, while the wire-mesh technique may not be useful for fine fraction estimations, they could still excellently serve the purpose as fine fraction separators under these conditions. This forms the fundamental rationale for exploring the combination of a wire-mesh capped passive deposition sensing technique to serve solely as the coarse fraction detector.

Motivated by the considerations above, we developed a progeny coarse fraction deposition detector, which consists of a wire mesh capped over the deposition sensing (Fig. 1) element, namely, the absorber mounted nuclear track detector. The latter, named as direct thoron/radon progeny sensors (DTPS/DRPS) has been well characterized in our earlier studies (Mishra et al., 2009a). The first part of the experimental work describes the optimization development and calibration of this capped arrangement. The second part deals with

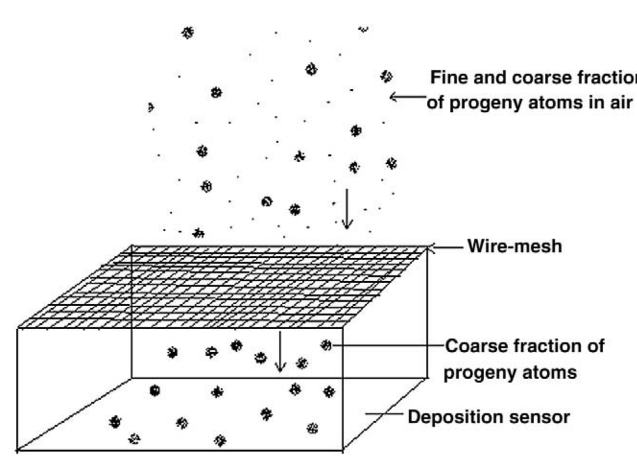

Fig. 1. Schematic diagram of the operation of the capped system.