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RESIDENTIAL RADON-222 EXPOSURE AND LUNG CANCER: EXPOSURE ASSESSMENT METHODOLOGY

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Although occupational epidemiological studies and animal experimentation provide strong evidence that radon-222 (^{222}Rn) progeny exposure causes lung cancer, residential epidemiological studies have not confirmed this association. Past residential epidemiological studies have yielded contradictory findings. Exposure misclassification has seriously compromised the ability of these studies to detect whether an association exists between ^{222}Rn exposure and lung cancer. Misclassification of ^{222}Rn exposure has arisen primarily from: 1) detector measurement error; 2) failure to consider temporal and spatial ^{222}Rn variations within a home; 3) missing data from previously occupied

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2. Abbreviations: ASD, activity-size distribution; ATD, alpha track detector; BEIR, biological effects of ionizing radiation; COV, coefficient of variation; DL, driver's license; DM, dosimetric model; ER, equilibrium ratio; HCFA, Health Care Financing Administration; HRD, historic reconstruction detectors; IRLCS, Iowa Radon/Lung Cancer Study; MARE, mean absolute relative error; pCi/L, picocuries/liter; QA, quality assurance; ^{222}Rn, radon-222; SEER, Surveillance, Epidemiology, and End Results; SHRI, State Health Registry of Iowa; EPA, U.S. Environmental Protection Agency; WLM, working-level month.

3. Key Words: dose, epidemiology, exposure, lung cancer, methodology, radon.

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homes that currently are inaccessible; 4) failure to link ^{222}Rn concentrations with subject mobility; and 5) measuring ^{222}Rn gas concentration as a surrogate for ^{222}Rn progeny exposure. This paper examines these methodological dosimetry problems and addresses how we are accounting for them in an ongoing, population-based, case-control study of ^{222}Rn and lung cancer in Iowa.

INTRODUCTION

Epidemiological case-control studies of radon-exposed underground uranium and hard-rock miners have shown that exposure to radon-222 (^{222}Rn) decay products is a causative factor in the development of lung cancer (NRC, 1988; Lubin et al., 1995). The dose-response relationship for cumulative ^{222}Rn decay product exposure exhibited a linear trend in the miner studies (Lubin et al., 1995), suggesting that even lower-level chronic residential ^{222}Rn progeny exposure may carry some risk. Numerous epidemiological studies, using either ecological or case-control designs, have been conducted to assess whether an association exists between residential ^{222}Rn exposure and lung cancer (Borak and Johnson, 1988; Samet, 1989; Neuberger, 1991, 1992).

Ecological studies generally have correlated geographically based lung cancer rates with a mean ^{222}Rn concentration obtained from a limited number of ^{222}Rn "screening" tests conducted in a given area. The ecological study design has major limitations (Morgenstern, 1982; Piantadosi et al., 1988; Lubin et al., 1990; Stidley and Samet, 1993; Greenland and Robins, 1994; Piantadosi, 1994) and cannot assess an individual's current or retrospective ^{222}Rn exposure. Because of these limitations, the 1989 Study Design Group of the International Workshop on Residential Radon Epidemiology concluded that, "Unless a special situation or unique data warrant conducting such a study, future ecological studies are not recommended" (U.S.DOE and CEC, 1989) for the study of residential ^{222}Rn risk.

Case-control studies can overcome many of the limitations of ecological studies and have been utilized to assess the relationship between residential ^{222}Rn exposure and lung cancer (Borak and Johnson, 1988; Samet, 1989; Neuberger, 1991,1992). While the case-control study design relies on the availability of existing medical records pertaining to the disease under study, the absence of accurate historical exposure data weakens a study's ability to detect underlying associations and thereby document criteria for causality. In this paper we discuss some substantial ^{222}Rn dose assessment methodological problems associated with case-control studies examining the relationship between ^{222}Rn exposure and lung cancer. We also present a methodological overview of an ongoing, population-based study of Iowa women, that specifically addresses the steps taken to overcome these methodological shortcomings.

METHODOLOGICAL PROBLEMS WITH ^{222}RN DOSE ASSESSMENT

Case-control studies examining the relationship between residential ^{222}Rn exposure and lung cancer present distinct and formidable obstacles related to accurate ^{222}Rn exposure assessment (Lubin et al., 1990).

Problem 1: Accuracy and Precision of Contemporary ^{222}Rn Gas Measurement

An important consideration in assessing a cumulative ^{222}Rn exposure is ^{222}Rn detector measurement error. Charcoal canisters and alpha track detectors (ATDs) are the primary types of ^{222}Rn detectors that have been used for ^{222}Rn measurements in epidemiological studies. Charcoal canisters provide a short-term screening ^{222}Rn measurement (two to seven days), while ATDs deliver a longer-term (two-month to one-year) integrated ^{222}Rn measurement. Although the accuracy of these detectors generally is within a mean absolute relative error (MARE) of 25% and a coefficient of variation (COV) of 10% for precision, the error frequently is greater (Field and Kross, 1990; EPA, 1991; Martz et al., 1991; Scott and Robertson, 1991; Yeager et al., 1991).

Good professional practice dictates that environmental measurements for a study adequately be conceived, documented, and executed so that the resulting data can be used with a high degree of confidence (EPA, 1980). It is imperative that the dosimetry used in epidemiological studies follow established quality assurance guidelines. These guidelines must include internal quality control checks for detector accuracy, detector precision, ^{222}Rn exposure occurring outside the placement period, detector placement, and detector reliability (EPA, 1980, 1992, 1993). Many epidemiological studies inadequately assess, document, and report their detectors' accuracy and precision. In addition, few studies document steps taken to ensure that the detectors remain appropriately placed during the entire monitoring period. Finally, complete quality control and quality assurance procedures rarely are described adequately in epidemiological studies.

Problem 2: Temporal and Spatial Variation of Residential ^{222}Rn Concentrations

Many of the national and international residential ^{222}Rn epidemiological studies have performed ^{222}Rn gas measurements for periods as short as one week to as long as one year (Neuberger, 1991; Stidley and Samet, 1993). Because ^{222}Rn gas and progeny concentrations exhibit significant temporal variability, longer-term home ^{222}Rn measurements decrease ^{222}Rn dose misclassification resulting from short-term measurement. Indoor ^{222}Rn variations occur hourly, diurnally, monthly, and seasonally, and are influenced by numerous factors, including ^{222}Rn infiltration rates, heating/air conditioning system design and usage, pressure differentials, soil characteristics, weather conditions (e.g. rainfall, wind speed), and occupant behavior (Hess et al., 1985; EPA, 1990; Field and Kross, 1990; Steck, 1992). In fact, home ^{222}Rn variations exceeding a factor of five occur over time intervals as long as several years in the upper midwest (Steck, 1992).

The ratios of ^{222}Rn concentrations between and within the levels of a home are dependent on numerous factors, including ^{222}Rn infiltration rates, heating/air conditioning system design and usage, pressure differentials, water usage, weather conditions, occupant behavior, house construction, and temperature differentials. Preliminary findings of the Iowa Radon/Lung Cancer Study have noted ^{222}Rn concentrations differing by a factor of 20 in different areas of the same home.

Because of the magnitude of spatial and temporal ^{222}Rn variations within a home, significant sampling error occurs when short-term ^{222}Rn measurements are used to infer ^{222}Rn concentrations for a period of time exceeding the duration of the actual measurement. Table 1 presents a tiered classification of the most common epidemiological ^{222}Rn dose assessment methods. The majority of ^{222}Rn measurements used by homeowners for risk assessment and by epidemiologists for ecological studies are short-term screening samples taken at one location in the lowest livable level of the home (Tier 4). ^{222}Rn measurements used in many case-control epidemiological studies cover one year or less in one or two locations in a home (Tiers 2 and 3). The majority of ^{222}Rn epidemiological studies fall into Tiers 2,3, and 4. ^{222}Rn exposure misclassification increases from Tier 1 to Tier 4.

TABLE 1. Classification of Epidemiological ^{222}Rn Dose Assessments

Tier	Quality	Description
1	Advanced	One-year ^{222}Rn measurements in several areas of the home with linkage to the subject's temporal and spatial mobility
2	Intermediate	One-year home ^{222}Rn measurements
3	Basic	Less than one-year home ^{222}Rn measurements
4	Rudimentary	Surrogate ^{222}Rn measurements or screening ^{222}Rn measurements

The degree of temporal and spatial ^{222}Rn variation is of particular concern in ^{222}Rn epidemiological studies measuring homes that no longer are occupied by the participant. High mortality rates make this a special problem for case houses. It is likely that the mean home ^{222}Rn concentrations that exist after the participant no longer lives in the home are not reflective of ^{222}Rn concentrations that prevailed when he/she was in residence. Changes in ^{222}Rn concentrations may be caused simply by behavior differences between the new and former occupant, such as opening the windows more frequently. The new owner also may make structural changes in the home that affect ^{222}Rn concentrations, such as modifications of the heating system. It is noteworthy that Alavanja et al. (1994) failed to find an association between ^{222}Rn exposure and lung cancer in a Missouri-based radon/lung cancer epidemiological study of nonsmoking women. Yet when the researchers restricted the analyses to the 37% subgroup of living cases, a positive dose-response trend was noted. One reason an association was found in this subgroup may have been that their contemporary home ^{222}Rn concentrations were more representative of historical ^{222}Rn concentrations.

Problem 3: Missing Data Due to Inability to Measure Previous Homes

The current biological effects of ionizing radiation (BEIR) dose-response model (NRC, 1988) finds that risk is proportional to cumulative exposure. Although this model weighs exposures occurring 5 to 15 years in the past more heavily than earlier exposures, the effect of the exposure time in the distant past makes it important to reconstruct exposures beyond the 15-year interval. Because many residential studies try to obtain ^{222}Rn measurements for every dwelling occupied by the study participant over the previous 30 years, gaps in the participants' exposure history occur. These gaps seriously decrease the studies' statistical power to reveal an association (Lubin et al., 1990).

Problem 4: Missing Exposure Estimates Due to Occupancy Patterns

The variation of ^{222}Rn within the home can lead to serious exposure misclassification unless the spaces most frequently occupied are measured directly (Table 1, Tier 1). Most epidemiological studies have relied on ^{222}Rn measurements in one or two rooms to characterize the entire domestic exposure, without demonstrating that this characterization is adequate. To date, epidemiological studies have not attempted to link temporal and spatial home occupancy patterns with multiple ^{222}Rn measurements within a home, which would allow calculation of retrospective cumulative ^{222}Rn exposures over a given time period. Nor have studies attempted to gather information on historical cumulative ^{222}Rn exposures occurring outside the home.

Problem 5: Measuring ^{222}Rn Gas Concentrations as a Surrogate for ^{222}Rn Progeny Exposure

All major epidemiological studies examining the relationship between ^{222}Rn exposure and lung cancer have estimated the radiation exposure derived from ^{222}Rn progeny exposure by measuring ^{222}Rn gas concentrations in the participants' homes (Samet, 1989; Neuberger, 1991, 1992). Because ^{222}Rn decay products, rather than ^{222}Rn gas itself, deliver the actual radiation dose to the lung tissues (NRC, 1988), better residential radiation dose estimates for humans require the measurement of actual airborne ^{222}Rn decay product concentrations. To calculate the effective dose-equivalent to bronchial tissues from ^{222}Rn progeny in dwellings, it is necessary to know the activity-size fraction distribution of the airborne ^{222}Rn progeny.

Current dosimetric models (James, 1989; NRC, 1991) use effective-dose conversion factors that depend on aerosol size. Activity-size distribution (ASD) measurements made in a small sample of homes show a continuous distribution, with two, and sometimes three, major size fractions (Porstendorfer et al., 1987; Knutson, 1988; Li and Hopke, 1991; Wasiolek et al., 1991). The smaller-sized fraction (<10 nm in diameter), sometimes called the molecular fraction, has higher effective-dose conversion factors than the larger size fraction, often called the aerosol- attached fraction. The molecular-sized particles are quite mobile and are removed easily from the air when they come in contact with a surface. The aerosol-attached particles tend to remain in the air longer than the molecular-sized particles. The ASD varies with changes both in ^{222}Rn concentrations and in the characteristics of the domestic atmosphere (Porstendorfer et al., 1987; Knutson, 1988). Both ^{222}Rn concentrations and these atmospheric

characteristics can change dramatically over short periods of time in response to natural or human activities (Reineking and Porstendorfer, 1990; Li and Hopke, 1991).

The manner in which the dose delivered to the lungs is partitioned between the size fractions is complex and not fully understood. In some circumstances, the enhanced nasal deposition of the molecular fraction, along with higher activity in the aerosol-attached fraction, can combine such that dose may be divided almost equally between the two fractions (Li and Hopke, 1991). The estimated partitioning is, however, quite sensitive to both the atmospheric conditions and the dosimetric model assumptions such as fraction of mouth-to-nose breathing, hygroscopic growth in the airways, etc. The dose to the airway tissues can be a factor of two higher or lower in the same room (Hopke et al., 1995) when the atmospheric conditions change. To obtain accurate dose assessment, it is vital to characterize the average ASD of the airborne radionuclides.

OVERVIEW OF THE IOWA RADON/LUNG CANCER STUDY (IRLCS)

The IRLCS is a five-year, population-based, case-control study that evaluates the association between exposure to residential ^{222}Rn and ^{222}Rn progeny and the incidence of lung cancer among females in the state of Iowa. The study is funded by the National Institutes of Environmental Health Sciences and is scheduled to end in October 1997. The IRLCS has four major components: 1) rapid-reporting of cases, 2) a mailed questionnaire followed by a face-to-face review and facilitated interview, 3) a comprehensive ^{222}Rn exposure assessment, and 4) independent histopathological review of lung cancer tissues. Iowa is an excellent location to perform such a study for several reasons: 1) a substantial proportion of Iowa's population resides in the same home for 20 years or more; 2) Iowa has a high-quality, National Cancer Institute–supported Surveillance, Epidemiology, and End Results (SEER) registry for cancer reporting which allows rapid identification of newly diagnosed lung cancer cases; and 3) Iowa homes contain the highest mean screening ^{222}Rn concentrations in the United States (White et al., 1992; Field et al., 1993).

Lung Cancer Case and Control Eligibility and Ascertainment

Lung cancer cases enrolled in the study meet the following eligibility criteria: 1) newly diagnosed between May 1, 1993 and April 30, 1996 with a microscopically confirmed, primary, invasive lung cancer without any prior lung cancer; 2) female Iowa resident at time of diagnosis; 3) 40 to 84 years of age; 4) either alive or deceased at initial contact (next-of-kin are contacted for deceased cases); 5) has resided for 20 or more consecutive years in the current home; and 6) has not made modifications to the home as a result of previous ^{222}Rn testing. An estimated total of 450 cases will be included in the study. Lung cancer cases are rapidly reported through the State Health Registry of Iowa (SHRI), a National Cancer Institute SEER Program participant since 1973 (Karnell et al., 1995). SHRI field representatives, using rapid-reporting, check all hospitals and laboratories in the state at least monthly for pathology reports of primary or suspected primary lung cancer. Thus far, rapid-

reporting has allowed for a median of 25 days between lung cancer diagnosis and SHRI identification.

Controls enrolled in the study meet the following eligibility criteria: 1) no prior malignant (invasive) lung cancer as determined by the SHRI data base; 2) no malignant lung cancer within the last two years as reported by the control at time of initial contact; 3) female Iowa resident; 4) 40 to 84 years of age; 5) alive at time of initial contact; 6) has resided for 20 or more consecutive years in the current home; and 7) has not made modifications to the home as a result of previous ^{222}Rn testing. An estimated total of 600 controls will be included in the study. Controls aged 40–64 are selected from current driver's license (DL) tapes provided by the Iowa Department of Transportation. Controls aged 65–84 are selected from Health Care Financing Administration (HCFA) records. Both DL and HCFA controls are age frequency–matched with the lung cancer cases by five-year age groups.

Histopathological Review

For each eligible case, two surgical pathologists from the Department of Pathology at the University of Iowa review pathological material upon which the lung cancer diagnosis was based to obtain a consistent histological diagnosis based on World Health Organization histological typing of tumors (WHO, 1982). The reviewers are blinded to the diagnosis on the pathology report, as well as to each other's review diagnosis. If the histological type of tumor designated differs between the two reviewers, they review the pathological material together and render a consensus diagnosis.

Questionnaire Instruments

A mail-out questionnaire is sent to each participant prior to a home visit. Participants complete the questionnaire at their leisure, thereby reducing fatigue and improving recall, since the participants are able to check their records. Detailed information is obtained on demographics, occupational history, occupational exposure to toxicants, smoking history (both active and passive), personal health history, family health history, vitamin usage, diet, cooking practices, home characteristics, drinking water sources, heating and cooling systems, ventilation patterns, weatherization, and other factors that may affect home ^{222}Rn concentrations. Particular attention is paid to historical changes in the home or in participant behavior that may affect ^{222}Rn concentrations over time.

Subsequent to consent and receipt of the questionnaire, a field research technician visits each study site to review the questionnaires for completeness, facilitate a mobility interview, and place dosimetry. They also record home floor plans, room location of detector placement, detector placement location within a room, house level of placement, time of placement, date of placement, detector control numbers, and household identification number on both a sample custody form and detector logbook. The technicians conduct an on-site residential assessment survey which documents home characteristics, location of rooms and dimensions, number of home levels, and environmental gamma levels. The field technicians chart each source of potential air flow, such as circulating fans, windows, cold air returns, and heat

supply ducts observed in each room where contemporary and historical progeny measurements are performed.

Dose Assessment Methodology

1. Accuracy, precision, and reliability of contemporary ^{222}Rn gas measurements. Landauer's Radtrak Alpha Track Detector (ATD) was chosen as the primary device to provide an integrated mean ^{222}Rn concentration of temporally varying residential ^{222}Rn gas concentrations. This particular long-term measurement device was selected for two reasons: 1) it provides superior accuracy and precision when compared to several other commercially available ATDs (Pearson et al., 1992), and 2) it exhibited excellent accuracy and precision in a recent epidemiological study of ^{222}Rn and lung cancer, performed in Missouri.[1]

A detailed written Quality Assurance (QA) Plan for the IRLCS is maintained at the University of Iowa. The plan includes QA information concerning receiving, tracking, editing, entering, and filing of study data. The dosimetry QA portion of the plan is guided by the following EPA publications where applicable: Interim Guidelines and Specifications for Preparing Quality Assurance Plans (EPA, 1980), Protocols for Radon and Radon Decay Product Measurements in Homes (EPA, 1993), and Indoor Radon and Radon Decay Measurement Device Protocols (EPA, 1992).

Five percent of study detectors are exposed to known ^{222}Rn concentrations to assess detector accuracy and precision; ten percent of the ATD placements have a collocated placement to test the precision of the measurement; and five percent of detectors are designated field control detectors (blanks). Long-term E-PERMs (Electret-Passive Environmental Radon Monitors), which are exposed for one year, also are collocated with study ATDs at about 5% of study homes and serve as a field intercomparison with the ATDs. All E-PERM placement locations are monitored for gamma background using a Ludlum Measurements, Inc., Model 19 micro R meter.

IRLCS study staff call participants at least twice during the year-long exposure period to assess whether detectors continue to be placed according to study protocols. A field research technician performs a termination survey at the end of the monitoring period to retrieve dosimetry and administer a final questionnaire that ascertains information on changes in home construction or behaviors that may have affected ^{222}Rn concentrations during the monitoring period. In addition, any detector movement from site of original placement is noted on the floor plan for the home. A QA officer from outside the study periodically reviews all aspects of ^{222}Rn measurements, including field procedures, data management, data collection, laboratory correspondence, data analyses, reports, and data archives.

To date, the IRLCS ATDs exposed to known ^{222}Rn concentrations in an EPA ^{222}Rn chamber have been well within the limits established for detector precision and accuracy by the EPA

[1]ALAVANJA, M. (1993). Personal communication. National Cancer Institute.

(EPA, 1991). Field control detectors, "blanks," have demonstrated that the detectors have not picked up any extraneous ^{222}Rn exposure either in the field or during shipment to the laboratory.

2. Temporal and spatial variation of ^{222}Rn concentrations. The IRLCS residential ^{222}Rn gas exposure assessment has two components: 1) a participant mobility interview and 2) measurement of on-site ^{222}Rn and ^{222}Rn progeny. The residential exposure assessments are conducted by three research technicians based in regionally dispersed areas of Iowa. To avoid the effects of temporal residential ^{222}Rn variation, contemporary ^{222}Rn gas concentrations are measured for a period of one year using up to seven Landauer ATDs per home and an average of four per home. In addition, ^{222}Rn gas measurements are performed in approximately 25% of study homes for a second year using new ATDs that replace the previous year's ATDs. These replacement ATDs are located in the participant's bedroom and in the lowest level of the home. They provide an estimate of the yearly residential ^{222}Rn variability.

In view of the short survival rate of lung cancer victims, many epidemiological radon/lung cancer studies are limited to placing the majority of detectors in the most recently occupied homes of now deceased cases (Neuberger, 1992; Alavanja et al., 1994). Of particular interest to the researcher is whether or not the mean home ^{222}Rn concentrations existing after the participant is no longer living in the home are representative of ^{222}Rn concentrations when she/he was in residence. The representativeness of ^{222}Rn concentrations that prevailed when the study participant was living in the house can be ascertained in the IRLCS with second year ^{222}Rn monitoring, because the proportion of the lung cancer cases still alive during the first and second year of the measurement period are 75% and 35%, respectively.

Spatial differences in residential ^{222}Rn concentrations are accounted for by placing up to seven detectors in each home, weighted by occupant mobility. At least one ATD is placed on each level of the home, in the participant's current bedroom, in the participant's historic bedroom(s), if applicable, and in the home work area, if applicable.

3. Missing data due to inability to measure previous homes. To be eligible for the IRLCS, a participant must have resided for 20 or more consecutive years in the current home. To date, the mean participant residency period is 32 consecutive years. This requirement for inclusion in the study eliminates missing data attributable to the inability to access homes occupied in the past twenty years.

4. Missing exposure estimates due to occupancy patterns. Historical participant mobility within the home, as well as time spent outside the home and in another building, is ascertained by a face-to-face interview with the study participant. Beginning with the year the participant moved into the current home, the interviewer prompts the participant to chronologically identify time periods where his/her mobility patterns remained relatively stable. Within the temporally stable time periods, hours spent in another building, outside, and within the home are collected using task-linkage (e.g., retrieval of hours based on time spent

involved in specific duties or activities). Each participant-reported time period is identified using autobiographical memory cues and facilitated using task-linkage, until the present (Brus et al., 1993). Using this methodology, all time (168 hours per week) is accounted for from the year of arrival in the current home until the present. Both a comprehensive contemporary and historic ^{222}Rn (and ^{222}Rn progeny) exposure assessments are obtained by linking in-home ATD ^{222}Rn measurements and historic ^{222}Rn measurements, described below, with participant mobility information.

The IRLCS, in addition to having the attributes of a Tier 1 study (Table 1), also systematically measures outdoor ^{222}Rn concentrations at 100 ambient measuring stations dispersed geographically across Iowa. The IRLCS's comprehensive ^{222}Rn gas and ^{222}Rn progeny monitoring, linked to the participant's temporal and spatial occupancy of the home, accounts for approximately 90% of the average participant's exposure. The only potential retrospective participant ^{222}Rn exposure that does not have a ^{222}Rn concentration to link with mobility is the time the participant spends in another building. Sensitivity analyses (imputational techniques) currently are underway to assess the effect of a theoretical range of "other building" ^{222}Rn concentrations on the overall participant exposure estimate.

5. Measuring ^{222}Rn gas concentrations as a surrogate for ^{222}Rn progeny exposure. A technique has been developed for reconstructing past ^{222}Rn progeny atmospheres that is inexpensive enough to be useful for dose assessment in an extensive survey. The technique relies on alpha activity that is implanted in and deposited on glass surfaces (Lively and Steck, 1993). A prototype of these historic reconstruction detectors (HRDs) was tested in the pilot project for the IRLCS (Steck et al., 1993).

These detectors use the same kind of track registration material routinely used in ^{222}Rn ATDs, using three chips. One chip, which is inside a filtered container, measures the contemporary ^{222}Rn concentration. The second chip measures the implanted surface alpha activity by being held in intimate contact with the glass. The third chip faces into the room and can distinguish between ^{218}Po and ^{214}Po deposited on its surface. Although this technique is more complicated and labor-intensive than conventional ^{222}Rn ATDs, the material cost per module is only slightly higher. The measured ^{222}Rn, ^{210}Po, ^{218}Po, and ^{214}Po activities are combined with room data in the model described below to reconstruct the contemporary and historical average doses. To our knowledge, these are the only inexpensive detectors available to reconstruct past and present ^{222}Rn decay product exposures.

Contemporary ^{222}Rn progeny measurements are expensive and difficult to perform directly. Measurements of the surface-deposited activity of two short-lived alpha emitters (^{218}Po and ^{214}Po) and the airborne ^{222}Rn concentrations are used to reconstruct a bimodal airborne ASD. The reconstruction model requires four atmospheric parameters: the surface-to-volume ratio, the air-exchange rate, the aerosol-attachment rate, and the particulate-deposition rate. The first two parameters are estimated from room characteristics and the latter two are determined from the surface-deposited activity measurements. The HRDs measure surface-deposited

activities over a one-year period in order to include atmospheric changes associated with the full range of domestic activities.

^{222}Rn and ^{222}Rn progeny exposure assessments can be extended to periods as long as several decades, using the above atmospheric parameters combined with measurement of a long-lived ^{222}Rn decay product, ^{210}Pb, that implants into room surfaces. The long life of ^{210}Pb provides a convenient integrating reservoir for reconstructing the average historical activities of both ^{222}Rn and its short-lived decay products. Part of the surface-deposited ^{210}Pb is implanted in glass, just below the surface, where it remains trapped for decades. One of the decay products of ^{210}Pb, ^{210}Po, is easier to measure than ^{210}Pb itself, since it emits an alpha particle. Thus, the implanted ^{210}Po activity can be combined with the atmospheric model to reconstruct ^{222}Rn decay product exposures in a room for as long as the glass has been in the room.

Two of these historic ^{222}Rn detectors are placed at each study home for a one-year exposure period. One HRD is installed in the subject's current bedroom, while the other is placed in a high-occupancy room on another level. The HRD is affixed to a historic glass piece with a known history.

Multifaceted Dosimetry Approach

To address the problem of ^{222}Rn exposure misclassification, a multifaceted approach to residential ^{222}Rn dose assessment has been developed that can be represented by the faces of a pyramid (Figure 1). There are three faces to the pyramid: 1) a ^{222}Rn gas exposure face; 2) a ^{222}Rn progeny exposure face; and 3) a ^{222}Rn dose face. Each face is tiered in a manner similar to Table 1. Moving up the pyramid, misclassification decreases as a greater portion of an individual's exposure is accounted for by improved measurement protocols. Measuring more of the lived-in spaces would elevate a protocol to a higher tier. Different residential studies have approached the problem of assessing integrated lifetime dose by measuring exposures over intervals that are short compared to a lifetime. An assessment that uses a longer measurement interval would be placed in a higher tier. Since a variety of measurements are being taken, it will be possible to compare the reliability of different tiers and faces and explore differences between cases and controls. An example of a rudimentary measurement would be a short-term measurement in the lowest level. An advanced measurement would be a year-long measurement in all spaces that were occupied for significant lengths of time. Though both examples might use the average ^{222}Rn concentration as the exposure variable, they differ on both spatial and temporal coverage.

Because screening measurements using E-PERMS are conducted in 30% of study homes, one can compare Tier 1 time- and occupancy-weighted annual average radon gas exposure with the lower-level room short-term measurements to illustrate exposure misclassification. Current radon–lung cancer models are cast in terms of integrated radon progeny exposure rather than radon gas exposure (NRC, 1988). The portioning of the radioactivity among the different species of radon progeny, often given as the equilibrium fraction, must be known in

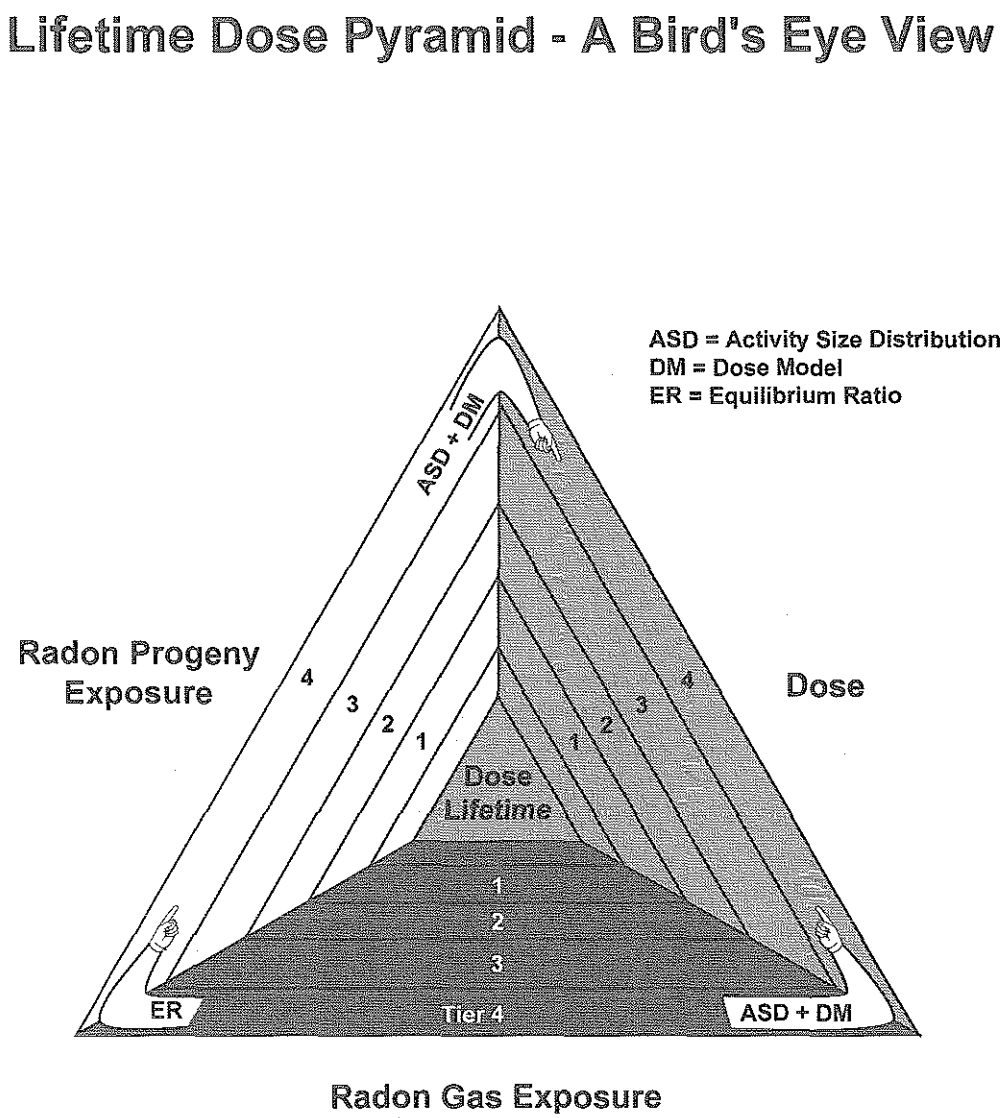

FIGURE 1. The ultimate goal of dosimetric assessment is a measure of the total dose related to the ^{222}Rn exposure received by an individual over a lifetime. Since direct measurements of this quantity are not feasible in a retrospective study, different measurement-modeling approaches have been taken to estimate the quantity. This figure illustrates the approaches and their interrelationships through tiers along each of three measurement-modeling faces. Along a given face, measurements with a higher fractional coverage of an individual's total exposure are placed on a higher tier. Most residential epidemiological studies use the ^{222}Rn gas (pCi/L) exposure face with an average concentration determined from contemporary measurements over a short time, while the underground miner studies use the radon progeny exposure face integrated over the workplace exposure interval expressed as working-level month (WLM). The faces can be related through modeling. For example, the equilibrium ratio (ER) connects the radon gas face to the radon progeny exposure face, while the ASD and a dosimetric model (DM) convert radon gas exposures to doses.

order to move from the radon gas exposure face to the radon progeny exposure face. Since HRD detectors can estimate the equilibrium fraction from deposited radon progeny, there will be a measure of an annual average radon progeny exposure in approximately two rooms per house, to compare with other radon assessments.

Calculating the dose requires a lung deposition model and a knowledge of the airborne ASD of the short-lived radon progeny. Since HRDs can estimate the bimodal ASD, contemporary and historical average radon progeny dose will be calculated for comparison with estimates produced from radon gas exposure measurements and "standard" assumptions about residential ASDs.

CONCLUSION

The IRLCS addresses many of the methodological problems associated with ^{222}Rn and ^{222}Rn progeny dose assessment. The modified exposure assessment methodology described above allows for the ascertainment of a substantial proportion of an individual's ^{222}Rn and ^{222}Rn progeny exposure. In addition, a major benefit of improving the linkage between measurement of ^{222}Rn and ^{222}Rn progeny and participant mobility is the reduction of personal ^{222}Rn exposure misclassification.

The IRLCS utilizes innovative techniques for estimating the cumulative radiation dose from persistent ^{222}Rn gas and ^{222}Rn progeny exposure. Through this framework we can compare the performance of the new methodology with the conventional techniques in the various tiers. Comparing the results of the above tier-exposure methods will improve the interpretation of short-term, limited coverage measurements and enhance the future ability to pool information from previous and contemporary epidemiological studies.

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