A Preliminary Model of Radon Exposure

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ABSTRACT

This paper develops a preliminary model of exposure to radon gases. It considers indoor and outdoor exposure to radon in residential and nonresidential settings. Differential exposure associated with level of activity, age, duration and seasonal variation are also considered. Dose equivalents to bronchial epithelium are estimated as the result of type of exposure, activity differentials, age differences, estimated length of exposure, and seasonal variation. The preliminary model of radon exposure draws on a variety of existing data relating to the social, technical and physical health characteristics of radon exposure.

KEYWORDS: Radon progeny, age dependency, time use, exposure, seasonal variation

INTRODUCTION

Exposure to naturally-occurring radon gas and its short-lived radioactive progeny has been used as a baseline radiation level for comparison with exposures from nuclear technologies and human-made sources of radiation. More importantly the problem of radon in the home is particularly significant because of the amount of time spent in the home, its significant health effects, and the social definition of the home as a "safe haven." Radon gas in homes is currently believed to be the cause of more deaths than all other types of radiation exposure combined, whether from natural or human-made sources (NCRP, 1984). The concentrations of radon in the home are an important consideration in determining exposure, as home "activities" account for the majority of people's time (Gesell, 1983; Nero, 1983; Cohen 1985). As appreciable time is also spent in non-residential buildings, radon concentrations in other indoor locations has also been considered (Cohen *et al.*, 1984). This paper considers indoor exposure to radon and its progeny, both in residential and non-residential settings, as well as outdoor exposures. In addition, this paper examines differential exposure associated with level of activity, age, duration and seasonal variation of exposure to radon and its progeny.

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BACKGROUND

Radon gas is present everywhere. It results from the radioactive decay of radium, which is part of the decay series beginning with uranium. "Significant amounts of radon—a natural radioactive gas—accumulate in our houses simply because we tend to build them on the largest source of radioactivity around: the ground" (Nero, 1986:28). A noble gas, radon has a half life of under four days, does not react chemically with surrounding materials, but can migrate into sources of air and water. Radon decays to a sequence of isotopes with short half lives: polonium-218, lead-214, bismuth-214, and polonium-214 (Nero, 1986:30). The health effects of radon are principally associated with these short-lived progeny (NCRP, 1984) because they are chemically active: depositing on airborne particulates, walls, furnishings and even the bronchial epithelium if inhaled. Once in the lungs, these isotopes are likely to complete the decay process to the next long-lived isotope, lead-210. This decay process irradiates the tissue surrounding the point of deposition. High concentrations of radon and its progeny have been associated causally with elevated lung-cancer rates among miners (Archer, 1978; Lundin *et al.*, 1971; Sevc *et al.*, 1976). The extent to which these high dose findings can be extrapolated to people exposed to lower doses is not known. This paper assumes a linear, no-threshold dose response model (NCRP, 1984).

TIME USE AND EXPOSURE LIKELIHOODS

Because exposure to radon varies with the amount of time spent in locations with various radon concentrations, exposure probabilities can be estimated from data on how and where people spend their time. Time budget analysis allows the analyst to determine the proportion of time spent in various locations that are subjected to different exposure rates. This paper focuses on the estimation of direct exposure to an ongoing hazard—radon and its progeny. The approach uses reliable data concerning the use of time by Americans to develop probability estimates of where people are and what they are doing for important exposure differentials.

In 1975, the Survey Research Center at the University of Michigan administered a time budget survey to a national probability sample of U.S. households (Robinson, 1977). The same households participated in a second panel of the same survey in 1981 (Juster *et al.*, 1983). In the 1975 survey, 1519 households were surveyed, which included 1519 respondents and 887 spouses. In 1981, attrition in the panel reduced the sample sizes to 620 households, with 620 respondents, and 376 spouses. The 1981 survey added the time budgets of children in the households. A comparison of 1975 with 1981 results indicates that the attrition in sample sizes caused little, if any, bias in the results. When demographic variables are controlled, these data indicate that the time budgets of U.S. households were amazingly stable over this period of time. The results in this study are from an analysis of the 1981 panel data. For both the 1975 and 1981 surveys, four waves were administered, one during each season of the year. For each wave, respondents and spouses were asked to construct a one day (24 hour) log of activities describing all activities the person engaged in during the previous day. Over the four waves of each survey, respondents reported their activities for two weekdays, and two weekend days. The 1975 survey contains 7207 person-days of data and the 1981 contains 3350 adult-days and 881 children-days. Most of the published reports of these University of Michigan data are based on an aggregated "synthetic week" (Stafford and Duncan, 1978 and 1980; Stafford, 1980). The two weekdays and two weekend days are combined and weighted to estimate how Americans spend time in an average week during the year. For some risk analyses the synthetic week approach does not provide enough detail about the daily schedules of people, which are critical in determining probability distributions of people at specific locations at fixed points in time. The preliminary model of radon exposure presented here examines the probability distributions for fixed locations, summing over seasonal and annual periods, to describe the probability distribution for those periods. The raw time log records contain, in part, the

Table
Percent of

Season	Age	Home Asleep
Winter	3-5	42.19
Winter	6-15	38.40
Winter	16+	34.35
Spring	16+	35.72
Summer	3-5	44.91
Summer	6-15	41.17
Summer	16+	36.18
Fall	16+	33.60

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MODELING RADON EXPO

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Table 1. Time Budgets: U.S. Population —
Percent of Time by Place, Season and Age Groups

Season	Age	Home Asleep	Home Awake	Indoors Other	Out-doors	Transit	NEC	Total
Winter	3-5	42.19	19.84	12.26	1.19	2.19	22.34	100
Winter	6-15	38.40	22.06	25.27	2.93	2.91	8.42	100
Winter	16+	34.35	32.70	23.82	2.43	5.30	1.40	100
Spring	16+	35.72	31.40	21.05	5.38	5.88	0.57	100
Summer	3-5	44.91	17.45	11.85	1.28	3.31	21.21	100
Summer	6-15	41.17	23.51	19.39	4.55	4.10	7.28	100
Summer	16+	36.18	33.05	19.54	4.37	5.82	1.04	100
Fall	16+	33.60	31.02	27.74	1.76	5.50	0.37	100

following items: respondent identification number, day of week, month, date of interview, activity code (a typology of 233 detailed activities), time activity began, time activity ended, secondary activity code, and elapsed time for activity. Typically, about 30 records describe the activities for a respondent for each day. These raw data are processed in two ways to form a period-activity data structure.

The Michigan time budget activity codes cover 233 detailed activity types. The detail is best illustrated by a few examples. Activities in the home, such as meal preparation, are broken down into several subcategories including cooking, cleanup, and other. Transit activities include subcategories of travel to and from work, travel in search of employment, to and from shopping, and to and from day care facility. Both primary activities and secondary activities are recorded. Primary activities dominate a particular period, while secondary activities are engaged in simultaneously with primary activities, e.g., listening to the radio while preparing a meal. To use these data in the estimation of radon gas exposure, they are collapsed from 233 activity codes to 6 broader categories reflecting an activity-location structure. The collapsed activity codes are: 1) at home asleep, 2) at home active, 3) indoors other, 4) outdoors, 5) in transit and 6) not elsewhere classified (NEC).[a] Table 1 summarizes the percent of time spent in these activities by season of the year and age groups. Thus:

> The most dominant feature of the average annual time budget is being at home asleep. Comprising 34.8 percent of an individual's total daily time on average.... The second most dominant feature of the annual time use budget is the time being active in the home. This primary activity comprises 23.9 percent of the typical day. Together, in-home active and asleep categories account for 58.8 percent of the total daily activity of adult Americans (Hummon *et al.*, p. 368, 1987).

MODELING RADON EXPOSURE

The predominant contributions to absorbed dose to the bronchial epithelium are from the short-lived radioactive progeny of radon 222, namely, polonium 218 (halflife, 3.05

a. The not elsewhere classified category accounts for time that is not attributable to one of the other major categories, or time gaps in the respondent's time log.

Table 2. Absorbed Dose to Bronchial Epithelium from Radon Progeny Depends on Ten Factors in Addition to the Radon Concentration (Adapted from NCRP, 1984)

	Unattached fraction of polonium 210
	Degree of radioactive equilibrium among progeny
	Particle deposition models
	Particle size distribution
	Physical dose calculation
*	Breathing pattern as a function of activity level
*	Bronchial morphometry as a function of age
	Mucociliary clearance rate
	Mucus thickness
	Location of target cells
*	Denotes the factors emphasized here.

Table 3. Pittsburgh Radon Concentrations

Location:	Home Basemt	Home 1st Fl	Home 2nd Fl	Indoors Other	Out-doors
Radon-222, pCi/L	6.33	2.37	2.01	0.49	0.34
Average:	Annual	Annual	Annual	Annual	Summer
GSD	2.10	2.35	2.60	2.11	1.64

Winter/Summer = 1.6 (Cohen, 1986)

minutes), lead 214 (26.8 minutes), bismuth 214 (19.7 minutes), and polonium 214 (0.00016 seconds). The absorbed dose can be inferred from concentration measurements of radon 222, but such inference requires the knowledge or assumption of many factors, as shown in Table 2 (adapted from NCRP, 1984). We examine the dose as a function of location, age, and level of physical exertion for a hypothetical population exposed to radon 222 levels such as those measured in Pittsburgh, Pennsylvania.

While some authors have reported no significant variations of indoor radon with seasons (George and Breslin, 1980), most authors report three-fold variations from summer to winter (UNSCEAR, 1982, Annex D). These variations are due to the decreased indoor-outdoor air exchange rate in the winter, and open windows in the summer. Cohen reports that the average ratio of indoor radon concentration from winter to summer is 1.6. We assume that spring and fall values are geometric means of these values, and equal to the annual average value. For scaling average annual indoor radon concentrations, we use factors of $1.6^{1/2}$, 1.0, $1.6^{-1/2}$, and 1.0 for winter, spring, summer, and fall, respectively (Cohen and Gromicko, 1986). Outdoor radon levels are taken as constant (UNSCEAR, 1982). Radon concentrations at home, in public buildings and outdoors are presented in Table 3. These concentrations, which account for location and season of the year, are used throughout this work (Cohen *et al.*, 1984; Cohen, 1985).

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Table 4. Scaling Factors for Various Levels of Physical Activity

	Volume	Frequency	Correction Factor*
Resting	1	1.0	.64
Light Activity	2	1.5	1.00
Heavy Work	3	2.0	1.44

*Correction factor is derived from Hofmann *et al.* (1979), and is discussed in detail in the text.

The amount of radioactivity inhaled depends on the number of breaths per minute and the volume per breath; both are functions of the level of physical activity (Table 4). The physical activity correction factors in Table 4 are derived from the work of Hofmann *et al.* (1979) by computing the product of respiratory frequency, tidal volume, and fractional retention of radon progeny in the tracheo-bronchial (TB) region and the pulmonary (P) region of the lung, as specified in the ICRP lung model (ICRP, 1975).

We have used the values of Hofmann et al. for the TB region (as opposed to the pulmonary region) in our calculations, since most radiogenic lung cancers have been seen in the upper airways, primarily in Weibel generations 2-10 (NCRP, 1984). The more recent calculations of Harley and Pasternak (1982) were not used because they do not encompass a comprehensive range of breathing rates, that is, there are no values available for heavy work. At least some time is spent by average people in heavy work such as shoveling snow, mowing grass, raking leaves, bicycling, jogging, exercising, etc., and the higher intake rate should not be ignored. The Harley and Pasternak numbers show only an average of 1.34 times as much dose for "active" adult males as for "resting" adult males, while the Hofmann numbers show 1.56 times as much dose for "light activity" and 2.25 times as much dose for "heavy work."

The two fundamental components of the model are (a) the concentration of radon gas and its progeny in various locations, and (b) the disposition of chemically active progeny attached to airborne particulates in the lung. This analysis uniquely uses the time budget data to estimate the extent to which people spend time in areas likely to have concentrations of radon progeny on the one hand, and level of activity in which they are engaged on the other. Table 5 summarizes the mapping of radon gas concentrations and physical activity into the time budget activities in particular locations. These assumptions link the fundamental elements of the model via the time budget activity and reflected location. They are interpreted as percent of time spent in the activity exposed to locational concentrations (A) or physical activity distributions (B). For example, being at home asleep is 100% resting, and 60% takes place on the second floor, 35% on the first floor and 5% in the basement. The conditions set forth in Table 5 represent a baseline model.

Age-dependent Dose Modification Factors (ADMFs) have been adapted from Hofmann et al. and are shown in Table 6 (Hofmann *et al.*, 1979). These factors are consistent with those of the NCRP (NCRP, 1984) and take account of age-dependent differences in bronchial morphometry, mucociliary clearance rate, breathing rate and deposition. They are normalized to a model 30-year old male used in radiation dosimetry and known as "Reference Man" (ICRP, 1975), so that a dose calculated for Reference Man can be multiplied by the ADMF to estimate the dose to an individual of a different age.

Some additional miscellaneous assumptions complete the model. We assumed a 50% equilibrium factor, resulting in a conversion factor of 0.005 WL/[pCi/L of radon-222]. The

Table 5. Mapping Radon Concentration and Physical Activity Data into Time Budget Data (Baseline Model)

	Percent of Time Budget Activity							
	A. Location					B. Physical Activity		
	Home							
Activity	Basement	1st Floor	2nd Floor	Other Indoor	Outdoors	Resting	Light Activity	Heavy Work
Home Asleep	5	35	60			100		
Home Awake	15	70	15				90	10
Indoors Other				100			80	20
Outdoors					100		50	50
Transit					100		100	
NEC				100			100	

Table 6. Age-dependent Dose Modification Factors (Adapted from Hofmann *et al.*, 1979)

Age	ADMF
0-2	1.7
3-5	2.2
6-16	1.9
16+	1

WL is the "Working Level," a measure of potential alpha energy concentration in air (NCRP, 1984). For Reference Man in an environmental atmosphere, we used the NCRP factor of 0.7 rad/WLM, where the WLM is the "Working Level Month," exposure to one WL for a 170-hour "occupational month" (NCRP, 1984). To correct for environmental exposures, we used a factor of 8766 hours per year divided by 170 hours per occupational month = 51.6 occupational months per environmental year, followed by the self-evident conversion of 0.25 year/season. We have adopted the dose-equivalent to absorbed dose Quality Factor, Q = 20 rems/rad (NCRP, 1984).

COMPUTATION AND ESTIMATION

A dose equivalent for each age group and each time budget activity was computed by mapping the radon concentrations versus location in Table 3 into the time budget activity categories in Table 5, part A. Each location-weighted time budget activity was further modified by the physical activity percentages in Table 5, part B, using physical activity correction factors in Table 4. The result was multiplied by the ADMFs in Table 6.

Table 7. Seasona

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Table 7. Seasonal Annual Dose Equivalents (rems) to Bronchial Epithelium in Pittsburgh

	Season				
Years of Age	Winter	Spring	Summer	Fall	Total
3-5	3.58		2.18		
6-16	3.14		2.04		
16+	1.91	1.49	1.21	1.47	6.07

A seasonal dose equivalent was computed by summing overall time budget activities, and an annual dose equivalent was computed by summing overall seasons.

The resulting exposure to radon and its progeny is 6.07 rems annual adult dose equivalent to the bronchial epithelium (Table 7). The present estimates are limited to Pittsburgh (due to the lack of detailed radon concentration data for the nation). The estimated rate is 2 times greater than existing national estimates of 3 rems annual adult dose equivalent (NCPR, 1984). The first floor radon concentrations in Pittsburgh (Cohen, 1985) are very similar to reported rates in other parts of the country, such as Central Maine, and the Pacific Northwest (Nero *et al.*, 1986), but the distribution by location, required to link the time budget data, is not available.

While estimates of exposure for children under 3 to 5 years of age and 6 to 16 years of age in the spring and fall were not possible (due to the lack of time budget data for children in the spring and fall) the winter and summer estimates alone provide 5.76 and 5.18 rems dose equivalence. These winter and summer estimates combined represent half the year, even though they do not represent half the annual dose equivalent. Even so it is apparent that the exposure for children is very high, if they are exposed at all during the spring and fall quarters of the year. For example, an additional .75 rem in each of these quarters, a dose equivalent of more than a third lower than any in Table 7, would result in estimates of 7.26 and 6.68 rems per year, respectively.

Analysis indicates that minor modifications in the model assumptions, say less than 10% of the values in Table 5, create very little variation in the resulting estimates. For example, shifting physical activity while home awake from 90% light activity and 10% heavy work, to 80% light activity and 20% heavy work, or to 100% light activity changes the resulting estimates about +2.5%.

The baseline model results in an annual adult dose equivalent of 6.07 rems to the bronchial epithelium (Table 7), while these two models estimate the annual dose at 6.22 and 5.92 respectively. Even fairly significant alterations in the assumptions have relatively minor impact on the resulting dose estimates. By assuming that no time is spent in the basement, where concentrations are highest, and equally splitting time spent at home awake between 1st and 2nd floors, even though 2nd floors are most often bedrooms where more limited waking time is spent, and ignoring whether half the houses in the United States even have a second floor, the annual adult dose equivalent declines to 5.19 rems, or a decline of about 14.6 percent. Similarly, equally proportioning the time spent home awake among the basement, 1st floor and 2nd floor, a condition that comes closer to reflecting the trend of basement game and family rooms, including exercise facilities, raises the dose equivalent rate about 13% to 6.87 rems per year for the average adult.

Table 8. Percent of Dose Received by Time Budget Activity, Age Group and, Season

Age	Season	Home Asleep	Home Awake	Indoors Other	Out-doors	Transit	NEC	Total
3-5	Winter	44.6	42.3	4.6	0.4	0.5	7.7	100
3-5	Summer	48.6	38.1	4.6	0.4	0.8	7.5	100
6-16	Winter	40.0	46.3	9.3	0.8	0.7	2.9	100
6-16	Summer	41.2	47.4	6.9	1.3	0.9	2.4	100
16+	Winter	30.9	59.4	7.6	0.6	1.1	0.4	100
16+	Spring	32.6	57.9	6.8	1.4	1.2	0.2	100
16+	Summer	32.1	59.2	6.1	1.1	1.2	0.3	100
16+	Fall	31.2	58.0	9.1	0.5	1.2	0.1	100

This model of radon exposure is unique because it links the examination of where people are and what they are doing with the greatest contribution to the dose. Table 8 presents the percent of dose received by activity/location, season, and age group. The dominant location of radon exposure is clearly in the home. Children receive more than 85% of their overall exposure at home. Adults receive around 90% of their overall exposure at home. Adults receive the largest amount of exposure while at home awake, while children receive the majority of their overall dose while sleeping. This stems from differential amount of time spent at home asleep by adults and children (Table 1). The adult dose is heavily concentrated while awake at home (59.4% in winter[b]). Using the winter season as a bench-mark, the home asleep category accounts for the second largest exposure rate (30.9%) for adults. Other indoor locations account for 7.6% of the exposure, while other activities including transit, outdoors and not elsewhere classified account for the remaining part of the dose (2.1%) in winter. The primary source of the seasonal exposure variation was found to be the differential concentrations in the homes. The variation in time budget activity by season of the year does have an impact, although it is quite small. Hence, the overall estimates of exposure are largely dependent on time budget activity, with significant variations by age of individual and season of the year.

CONCLUSIONS AND IMPLICATIONS

The most important finding of this preliminary model of exposure to radon and its progeny is that the majority of the dose is received at home. For adults, activities while awake at home dominate exposure at home, while for children time spent sleeping seems to be most important. The differences in exposure by age stem from two primary sources: age-dependent dosimetry and age dependent time use. These differences lead to a significant variation among the age groups available, even though the model was unable to characterize exposure for "infants," due to the lack of time use data. Seasonal variations in time use do not significantly affect proportions of doses received, although seasonal variation in radon concentration engenders significant seasonal variation in dose equivalent. Concern over radon and its progeny in the home is certainly justified by the exposure estimates presented herein.

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b. The other seasons are similar although lower. All seasons are reported in Table 8.

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Out-doors	Transit	NEC	Total
0.4	0.5	7.7	100
0.4	0.8	7.5	100
0.8	0.7	2.9	100
1.3	0.9	2.4	100
0.6	1.1	0.4	100
1.4	1.2	0.2	100
1.1	1.2	0.3	100
0.5	1.2	0.1	100

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certainly justified by the exposure

eported in Table 8.

Measurement of radon concentrations in homes is extremely important. This preliminary model indicates that sample measurements should be taken where dose is greatest. For example, if there are no children in the home, measurements should be taken in the living areas of the home. If children, particularly young children, are living there, measurements in sleeping areas are very appropriate. Finally, because radon concentrations are quite large in the basement, families spending significant time in basement living areas should be encouraged to place samplers in these areas. Because radon and its progeny are a naturally occurring phenomenon, they represent a national problem, affecting millions of households, perhaps being second only to smoking as a cause of lung cancer. EPA has recommended a limit of 0.02 WL for homes (USEPA, 1986). An examination of policy alternatives is appropriate, but beyond the scope of this paper. Such alternatives might include building code limitations on basement use, or requiring ventilation systems in new houses in affected areas, or providing tax incentives for families to retrofit existing homes, limiting or regulating underground housing in some areas. The estimates of exposure to radon are indeed significant; further study including the examination of policy alternatives is certainly indicated.

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Power-Frequency F

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ABSTRACT

The issues of whether and
fields are complicated by evider
human health, those effects may r
intensity of exposure. This paper
many physical quantities that desc
encounters with fields and possib
defined in the power-frequency co
people's exposure to transmission
"more is worse" measure of dose.

KEYWORDS: Sixty hertz, expo
magnetic fields

INTRODUCTION

Power-frequency (50/60 H
components of the power system
distribution circuits, household a
electrical currents in the body b
charges on power lines or househo
charges in the body. The changin
eddy currents in the body by Far
power lines and appliances can
automobiles, fences, and the chass
objects typically results in a pow
contact point. Enough is known
fields produced by various source
induced in different exposure situa

Only a couple of decades
frequency fields might affect hum
the public agenda and consumes re
millions of dollars per year. Con
have their most direct origins in
1960's. These lines not only tra

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