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Exposure to Atmospheric Radon

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We measured radon (^{222}Rn) concentrations in Iowa and Minnesota and found that unusually high annual average radon concentrations occur outdoors in portions of central North America. In some areas, outdoor concentrations exceed the national average indoor radon concentration. The general spatial patterns of outdoor radon and indoor radon are similar to the spatial distribution of radon progeny in the soil. Outdoor radon exposure in this region can be a substantial fraction of an individual's total radon exposure and is highly variable across the population. Estimated lifetime effective dose equivalents for the women participants in a radon-related lung cancer study varied by a factor of two at the median dose, 8 mSv, and ranged up to 60 mSv (6 rem). Failure to include these doses can reduce the statistical power of epidemiologic studies that examine the lung cancer risk associated with residential radon exposure. *Key words*: outdoor exposures, radiation, radon. *Environ Health Perspect* 107:123–127 (1999). [Online 12 January 1999]

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Prolonged exposure to high concentrations of radon decay products has been associated with increased lung cancer risk for humans. Although studies of underground miners have provided estimates of radon exposure risks in homes, residential epidemiologic studies have produced statistically equivocal results (*1*). Most residential studies only measure the contemporary radon gas concentration in one or two rooms of a person's current home, even though an individual's risk is believed to be proportional to their cumulative radon exposure. These studies assume homogeneity of radon within the home and exposures outside the home that are relatively low and uniform. Recent sensitivity analyses suggest that errors or omissions in radon exposure assessment reduce the ability of epidemiologic studies with a small sample size to detect an effect, if one exists (*2,3*).

The worldwide, population-averaged radon concentration is estimated to be 10 Bq/m^3 (0.3 pCi/l) outdoors and 40 Bq/m^3 (1.1 pCi/l) indoors (*4*). In the United States, these averages are estimated to be 15 Bq/m^3 (0.4 pCi/l) outdoors (*5*) and 54 Bq/m^3 (1.5 pCi/l) indoors (*6,7*). Outdoor radon estimates are based on sparse, often short-term, measurements. Even in the United States, where the Indoor Radon Abatement Act (Public Law 100-551, 1988) establishes a goal of reducing indoor radon levels to local atmospheric levels, few long-term outdoor radon measurements have been made (*8,9*).

Methods

We investigated the relationship between indoor and outdoor radon as part of a case–control study, the Iowa Radon Lung Cancer Study (IRLCS) (*10*). We measured

annual average atmospheric radon concentrations at 111 locations in Iowa and 64 locations in Minnesota to assess the impact of radon exposures outdoors on overall cumulative radon exposures. Because IRLCS participants were selected from all parts of Iowa, we sampled uniformly across that state with sites separated by about 40 km (Fig. 1). In Minnesota, we investigated spatial variation over small and large distances by sampling counties adjacent to and distant from Iowa. Unlike the Iowa survey, most Minnesota counties had from 1 to 15 sites. Minnesota and Iowa counties are roughly 50 × 50 km in size. Minnesota is roughly 550 × 340 km and Iowa is 320 × 450 km.

Central North America has diverse physiography and climate. Most of the surface is covered by thick glacial till. Winters are extremely cold and summers are quite hot. The temperature varies spatially in such a way that the northernmost sampled areas have twice the heating degree-days but only 20% of the cooling degree-days as compared to the southernmost areas. Moderately high winds occur during most seasons. Precipitation is sufficient to support trees in the east but grasses dominate the west. This region is open and extensively farmed except for the forested areas north of 46° latitude and east of 92° longitude. The population in both states is roughly evenly divided between urban and rural dwellers.

In Iowa, IRLCS field personnel placed detectors outdoors in open areas starting in the fall of 1993 and extending through the winter of 1996. At each site, an alpha track detector was enclosed in protective housing and deployed at a height of 1.5 m for 1 year. The detector uses LANTRAK (Landauer, Inc., Glenwood, IL) enclosed in a 300-ml aluminum filtered chamber. The 2-cm^2 area

chips are etched for 6 hr at 75°C and read under 100× magnification until more than 150 tracks in three or more separate regions are counted. We repeated the year-long measurements at five sites to study year-to-year variation. At four sites, detectors were placed at heights of 1 and 2 m, respectively. In Minnesota, homeowner volunteers placed detector modules in their yards from November 1995 to December 1996.

We have determined that the random variation of our outdoor detectors for total exposures of 40 Bq years/m^3 (1.1 pCi-years/l) is approximately 10% by exposing groups of detectors in radon chambers and homes. In field exposures, 13 duplicate pairs showed a 7% coefficient of variation (COV) for year-long exposures to concentrations ranging from 10 to 50 Bq/m^3. A Wilcoxon signed-ranks test detected no statistically significant difference between the duplicate pairs (*p* = 0.2). Minor contamination from detector manufacturing and exposure during storage limit the lower level of detection to 4 Bq/m^3 for a year-long exposure. We exposed eight of our detectors along with five RADTRAK detectors side-by-side at one site where the annual average radon concentration was 10 Bq/m^3. The COV of our detectors was 14%, and the mean agreed within instrumental variation (4 Bq/m^3) with the mean of the RADTRAK cluster. Our outdoor radon detectors have been exposed in calibration and quality-control exercises conducted by the U.S. Department of Energy Environmental Measurements Lab (EML) and U.S. EPA Radon Measurement Program (RMP). The average relative error of our detectors was within -3% and -8% in two EML tests for annual-equivalent exposures at 20 Bq/m^3 and 30 Bq/m^3, respectively. In two RMP tests for
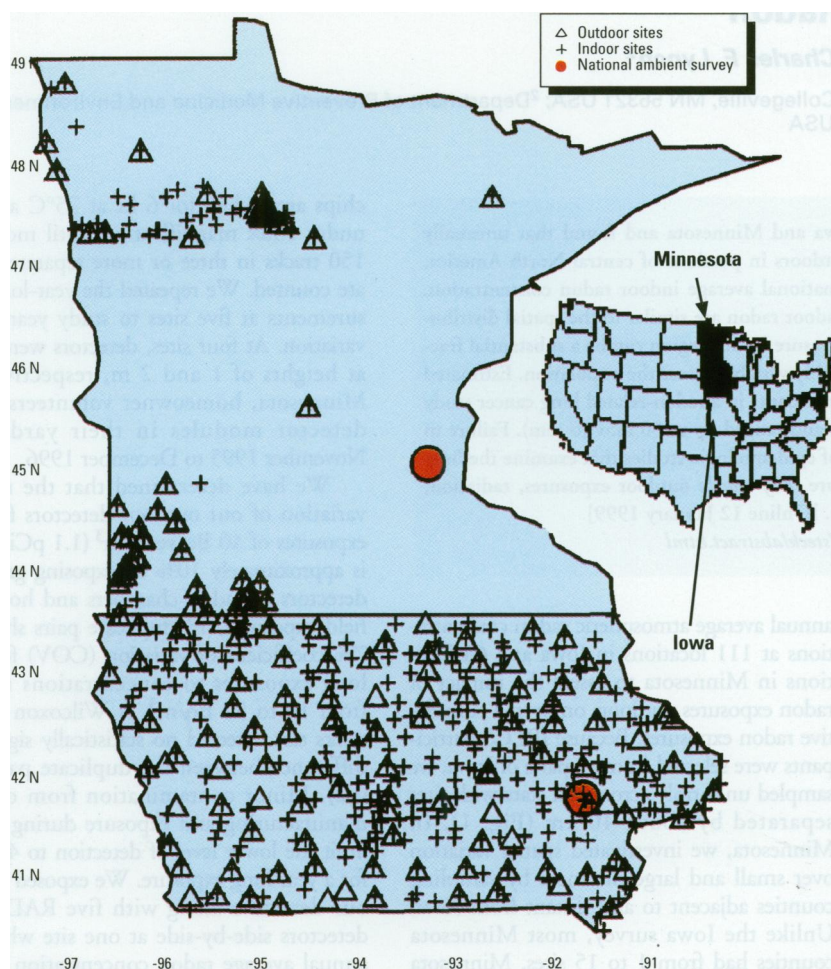
Figure 1. Sampling site locations. Data for the two locations sampled in the national ambient survey are from Hopper et al. (5).

Table 1. Statistical summary of annual average outdoor and indoor radon concentrations

Location	No.	GM[a] Bq/m³ (pC/l)	GSD	Average Bq/m³ (pCi/l)	Range Bq/m³(pCi/l)
Outdoor					
Iowa	111	29 (0.78)	1.4	30 (0.82)	7–55 (0.2–1.5)
Minnesota	64	19 (0.52)	1.8	22 (0.60)	4–55 (0.1–1.5)
Combined	175	25 (0.68)	1.6	28 (0.75)	4–55 (0.1–1.5)
Bedroom					
Iowa	1,039	90 (2.5)	2.2	124 (3.3)	7–1,100 (0.2–30)
Minnesota	128	100 (2.7)	2.2	142 (3.9)	18–1,200 (0.5–33)
Combined	1,167	91 (2.5)	2.2	126 (3.4)	7–1,200 (0.2–33)

Abbreviations: GM, geometric mean, GSD, geometric standard deviation.
[a]All distributions are log-normal.

annual-equivalent exposures of 10 Bq/m³ and 20 Bq/m³, the detectors were within -8% and +7% of the accepted value.

Indoor radon concentrations were also measured in homes located near the outdoor sampling points. The average annual radon concentration in the current bedroom of a subject (and up to six additional rooms) of 1,039 Iowa homes was measured with RADTRAK detectors as part of the IRLCS. Participants in that study also provided

detailed information about the time that they spent at different locations inside and outside the home (10). In Minnesota, 128 bedrooms were measured for radon concurrent with the outdoor survey.

Results and Discussion

Table 1 shows that high outdoor radon concentrations were found in a populated region of central North America. The high concentrations persist for a year or more

and cover substantial areas of Iowa and Minnesota. The median outdoor radon across this region (25 Bq/m³; 0.7 pCi/l) is about twice the national outdoor median (5). It exceeds the indoor medians for living areas as reported by epidemiologic studies in New Jersey and Connecticut (11,12). In Iowa, our measurements suggest that the population-weighted, average outdoor radon concentration is 28 Bq/m³. In some northwestern Iowa and southwestern Minnesota counties, the outdoor radon concentrations exceed the national average indoor radon concentration (6,7). Low outdoor radon concentrations (<10 Bq/m³) were observed in north-central Minnesota and in a few areas in eastern Iowa. The median indoor radon concentration in Iowa is also substantially higher than the U.S. national indoor median (6,7).

The results from both outdoor and indoor measurements matched well across the Iowa–Minnesota border despite the differences in sampling and protocol in these two states. Our results are in general agreement with the national ambient survey (NAS) results for Iowa City and Minneapolis (5). Although the outdoor average in Iowa exceeds the annual average of any site reported in the NAS, our measurements in Iowa City agree within aggregated instrumental, spatial, and temporal uncertainties (7 Bq/m³) with the measurements of the NAS. Our nearest measurement to Minneapolis (100 km) was within 2 Bq/m³ of the NAS result, and the value of the outdoor radon contour map derived from our data, as described below, is within 4 Bq/m³ of the NAS result.

The sampling density used in Iowa is sufficient for most radon assessment tasks, as we found that the small-scale spatial variation in Minnesota (within a county COV ~25%) is much smaller than the large-scale variation (statewide ~80%). This effect was observed in counties with high and low outdoor radon.

Elevated outdoor radon concentrations have been reported previously for a few locations. Most of those measurements covered shorter times or were associated with unusual localized surface geology or mining (13–19). A study in nearby Manitoba, Canada (20), observed elevated levels during one summer, but not the next. Although we have observed temporal changes of a factor of two during periods of unusual weather (see Fig. 2), we saw no significant year-to-year changes (<15%) at five sites. This observation is in agreement with other long-term studies (21–25). There was no significant difference between detectors placed at 1 and 2 m, in agreement with earlier reports (8,9,26–28).

To investigate spatial patterns, outdoor and indoor radon contour maps were constructed from the point data. These data were analyzed for directional correlation using the program VARIOWIN. The best VARIOWIN model established the parameters for a kriging algorithm on grid nodes separated by about 10 km in the contouring program SURFER. Patterns can be seen in those regions that were uniformly sampled, south of 43.5°N latitude. Figure 3 shows there is similarity in the spatial patterns of outdoor and indoor radon concentrations with elevated concentrations in western Iowa and in a band that extends southeasterly through southern Iowa. Note that areas of western Iowa have average outdoor concentrations comparable to indoor concentrations in areas of southeastern Iowa.

County-average, residual radon progeny concentrations in the soil (Fig. 4B) are highest in northwestern Iowa–southwestern Minnesota and lowest in north-central Minnesota (29,30). The same is true for outdoor (Fig. 4A) and indoor radon concentrations (map not shown). This pattern suggests that the local soils may play a significant contributory role to the elevated outdoor and indoor radon, even though their radon content is below the national average. These qualitative observations of pattern similarity are supported by significant correlation between the county medians of outdoor radon, indoor radon, and radon in the soil derived from the Minnesota point data sets. For example, there is moderately strong correlation between outdoor and indoor radon ($r = 0.7$; $p = 0.1$) for the six Minnesota counties with three or more outdoor and indoor measurements. On an individual site scale, the correlation was not significant ($r = 0.2$, $p = 0.2$ for 62 sites). In Iowa, where the radon in the soil does not vary as much as in Minnesota, the correlation was positive, but not significant ($r = 0.1$, $p = 0.3$).

Effective dose equivalents from outdoor radon in central North America can be significant. Radon-related dose models are still being refined, and the doses described here are estimates. Effective doses to the individual depend on many factors including radon concentration, exposure time, and the characteristics of the radon decay products. In particular, some locations can show significant diurnal radon concentration patterns, with high periods corresponding to the still early morning weather and low radon periods occurring during the turbulent late afternoon. However, the maximum, average hourly deviation from the mean at our two sites was only 15% for the site monitored for 55 days and 50% for the site monitored for 5 days. Many people in this region spend

considerable time outdoors engaged in work and recreation. In addition, outdoor exposure is more effective in delivering dose than

indoor exposure (4,31). The enhancement is due to the increased values for unattached radon progeny fraction (f_p), equilibrium
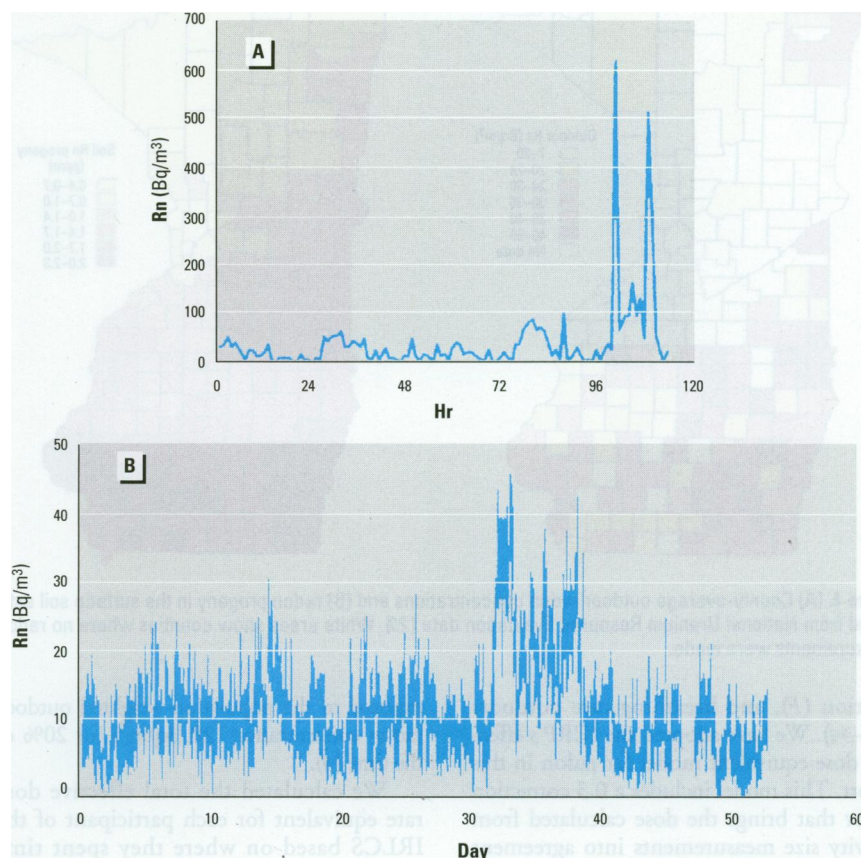

Figure 2. Short-term temporal variations of outdoor radon concentrations measured with continuous radon monitors. (A) Five summer days of hourly average radon concentrations at 1 m measured with a continuous radon monitor in southeastern Iowa; the unusual concentrations occurred during strong temperature inversions. (B) Fifty-three autumn days of hourly average radon concentrations measured with a continuous radon monitor in central Minnesota; the elevated concentrations occurred during a period of unseasonably warm, stable weather following a turbulent period. The short-term average radon concentrations were consistent within 8% of the year-long alpha track detector results at both locations.
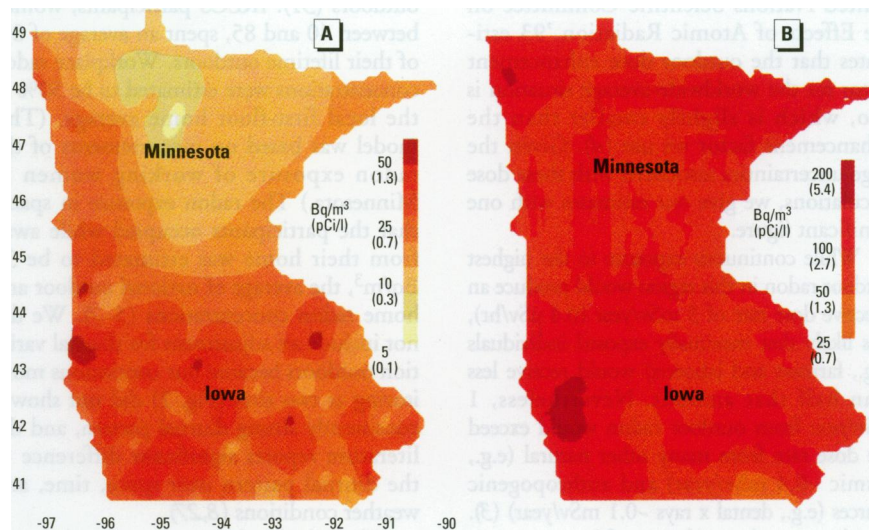

Figure 3. Radon contour maps. (A) Outdoor radon contour map. (B) Indoor radon contour map. Scales for A and B are color coordinated and logarithmic.
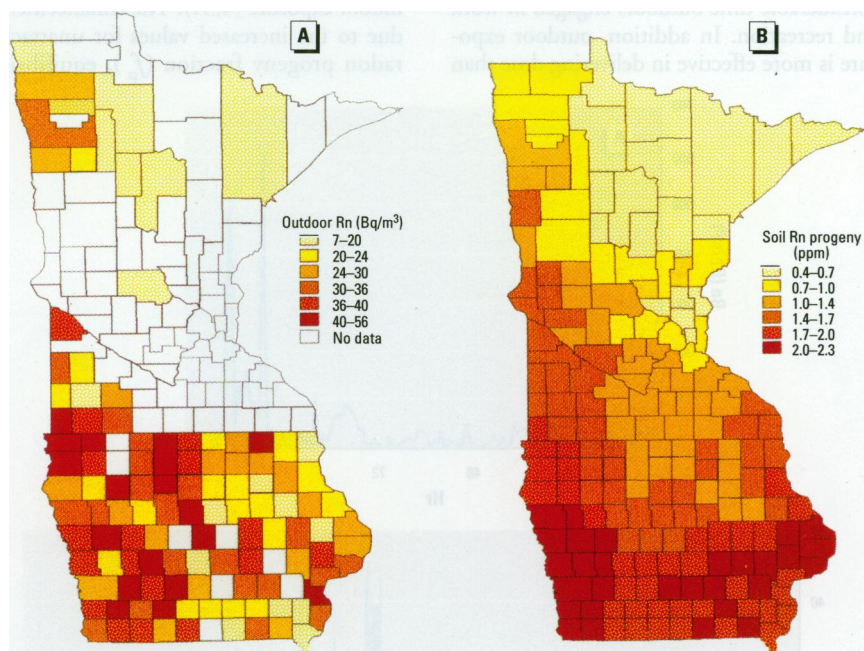
Figure 4. (A) County-average outdoor radon concentrations and (B) radon progeny in the surface soil estimated from National Uranium Resource Evaluation data (29). White areas show counties where no radon measurements were made.

fraction (F), and breathing rate outdoors (32–34). We have adopted the ICRP's effective dose equivalent model for radon in this report. This model includes a 0.3 correction factor that brings the dose calculated from activity size measurements into agreement with epidemiologic effective dose estimates. Recent measurements of atmospheric decay product characteristics in states near Iowa suggest that the effective outdoor dose equivalent rate is 6.7 nSv•hr⁻¹/(Bq•m⁻³). We also adopted the ICRP's dose rate effectiveness coefficient for indoor exposures, 2.3 nSv•hr⁻¹/(Bq•m⁻³) (31). We note that the United Nations Scientific Committee on the Effects of Atomic Radiation '93 estimates that the outdoor dose enhancement factor for the worldwide-average situation is two, which is slightly smaller than the enhancement factor we use (4). Given the large uncertainties associated with these dose calculations, we give our estimates with one significant figure.

While continuous exposure to the highest outdoor radon in this region would produce an effective dose rate of 3 mSv/year (0.4 µSv/hr), it is likely that maximally exposed individuals (e.g., farmers and laborers) would receive less than half that amount. Nevertheless, 1 mSv/year from outdoor radon would exceed the dose rate from many other natural (e.g., cosmic ~0.4 mSv/year) and anthropogenic sources (e.g., dental x rays ~0.1 mSv/year) (3). For the general population of Iowa, we estimate that the average effective dose equivalent rate would be 0.3 mSv/year based on being

exposed to the population-weighted outdoor radon concentration (28 Bq/m³) for 20% of the time (4).

We calculated the total effective dose rate equivalent for each participant of the IRLCS based on where they spent time (35), on measured radon concentrations in their home, and on estimates for the radon concentration in other locations. Outdoor doses were based on a local average for outdoor radon concentrations derived from our measurements, the ICRP effective equivalent dose rate coefficient reported for nearby states, and the individual's reported time outdoors (31). IRLCS participants, women between 40 and 85, spent an average of 8% of their lifetime outdoors. Workplace radon concentrations were estimated to be 50% of the local first-floor home average. (This model was based on measurements of the radon exposure of working women in Minnesota.) The radon exposure in spaces that the participants occupied while away from their home was estimated to be 35 Bq/m³, the average of national outdoor and home radon concentrations (5–7). We did not include an adjustment for diurnal variation outdoors because our continuous monitoring at two sites (Fig. 2) did not show a consistently strong diurnal pattern, and the literature reports significant difference in the diurnal pattern over space, time, and weather conditions (8,27).

The calculated dose rates were log-normally distributed, with a mean of 0.12 mSv/year and geometric standard deviation

(SD) of 2.0. For these participants, local outdoor radon contributed approximately 10%, on average, to their total radon-related effective dose rate. Outdoor dose rates accounted for 0–72% of an individual's total dose. Outdoor doses were higher than home indoor doses for 1% of the IRLCS participants.

Lifetime outdoor cumulative doses were calculated from the product of the local outdoor dose rate times the individual's age under the assumption that an individual lived her entire life in her current local area. Lifetime cumulative effective doses for outdoor radon were log-normally distributed, with a geometric mean of 8 mSv (800 mrem) and a geometric SD of 2.0. The maximally exposed individual in this group had a cumulative effective dose of 60 mSv as a result of spending 37% of her 76 years outdoors in 35 Bq/m³. Lifetime doses from all radon-related exposures ranged from 60 to 800 mSv. The average cumulative exposure was 150 mSv.

Outdoor radon concentrations of the magnitude and variability described in this report can reduce the validity and statistical power of an epidemiologic study. The work of Lubin et al. (2,3) suggests that the statistical power of a study such as the IRLCS to detect a risk of exposure to environmental radon is reduced by the omission of outdoor radon doses roughly proportional to the percentage of dose omitted. The exact magnitude of the loss of power will depend on the details of the analysis and the dose distributions. For example, if we separated the IRLCS participants into total radon-related dose rate quintiles rather than just domestic radon-related dose rate quintiles, then 60 of 407 (15%) of the cases and 75 of 610 (12%) of the controls would change classification quintile.

Conclusions

A failure to take outdoor doses into account could affect the results of other epidemiologic studies that have been conducted nearby, like those in Missouri (36) and Winnipeg (37), particularly if their participants spent more time outdoors than the IRLCS participants did. If accurate cumulative radiation dose assessment is important, then cumulative exposure estimates should include outdoor radon exposures.

REFERENCES AND NOTES

1. Lubin JH. Lung cancer and exposure to residential radon. Am J Epidemiol 140:323–332 (1994).
2. Lubin JH, Samet JM, Weinberg C. Design issues in epidemiologic studies of indoor exposure to Rn and risk of lung cancer. Health Phys 59:807–817 (1990).
3. Lubin JH, Boice JD Jr, Samet JM. Errors in exposure assessment, statistical power, and the interpretation of residential radon studies. Radiat Res 144:329–341 (1995).

4. UNSCEAR 93. Sources and Effects of Ionizing Radiation. Report to the General Assembly, United Nations Scientific Committee on the Effects of Atomic Radiation. New York:United Nations, 1993.

5. Hopper RD, Levy RA, Rankin RC, Boyd MA. National ambient radon study. In: Proceedings of the 1991 International Symposium on Radon and Radon Reduction Technology, 2–5 April 1991, Philadelphia, PA. Research Triangle Park, NC:U.S. Environmental Protection Agency, 1991.

6. Marcinowski F, Lucas RM, Yeager WM. National and regional distributions of airborne radon concentrations in U.S. homes. Health Phys 66:699–706 (1994).

7. Nero AV, Schwehr M, Nazaroff W, Revzan K. Distribution of airborne radon-222 concentrations in U.S. homes. Science 134:992–997 (1986).

8. Gesell TF. Background atmospheric ^{222}Rn concentrations outdoors and indoors: a review. Health Phys 45:289–302 (1983).

9. Harley JH. Radon is out. In: Proceedings of the 29th Hanford Symposium on Health and the Environment, 15–19 October 1990, Richland, WA:Batelle Press, 1992;741–763.

10. Field RW, Steck DJ, Lynch CF, Brus CP, Neuberger JS, Kross BC. Residential radon-222 exposure and lung cancer: exposure assessment methodology. J Expos Anal Environ Epidemol 6:181–195(1996).

11. Schoenberg JB, Klotz JB, Wilcox HB, Nicholls GP, Gil-del-Real, Stemhagen A, Mason TJ. Case control study of residential radon and lung cancer among New Jersey women. Cancer Res 50:6520–6524 (1990).

12. Weinberg C, personal communication, September 1997.

13. Pritchard HT, Gesell TF, Hess CT, Weiffenbach C, Nyberg P. Integrated radon data from dwellings in Maine and Texas. Health Phys 45:428–432 (1983).

14. Price JG, Rigby JG, Christensen L, Hess R, LaPointe DD, Ramelli AR, Desilets M, Hopper RD, Kluesner T, Marshall S. Radon in outdoor air in Nevada. Health Phys 66:433–438 (1994).

15. Amaral ECS, Rochedo ER, Paretzke HG, Franca EP. The radiological impact of agricultural activities in an area of high natural radioactivity. Radiat Prot Dosim 45:289–292 (1992).

16. Tyson JL, Fairey PW, Withers CR. Elevated radon levels in ambient air. In: Proceedings of the 6th International Conference on Indoor Air Quality and Climate, 4–8 July 1993, Helsinki, Finland. Helsinki:Helsinki University of Technology, Indoor Air '93, 1993;443–448.

17. Porstendorfer JP, Butteweck G, Reineking A. Daily variation of the radon concentration indoors and outdoors and the influence of meteorological parameters. Health Phys 63:283–287 (1994).

18. Kobal I, Vavpotic J, Burger J, Stegnar P. Preliminary measurements of indoor radon in Ljubljana, Yugoslavia. Radiat Prot Dosim 24:547–550 (1988).

19. Robe MC, Rannou A, Le Bronec J. Radon measurement in the environment in France. Radiat Prot Dosim 45:455–457 (1992).

20. Gratsy RL. Summer outdoor radon variations in Canada and their relation to soil moisture. Health Phys 66:185–193 (1994).

21. Smetsers RCGM. An automated gross alpha/beta activity monitor applied to time-resolved quantitative measurements of ^{222}Rn progeny in air. Health Phys 68:546–552 (1995).

22. Blaauboer RO, Smetsers RCGM. Outdoor concentrations of the equilibrium-equivalent decay products of ^{222}Rn in the Netherlands and the effect of meteorological variables. Radiat Prot Dosim 69:7–18 (1997).

23. Harley NH. Radon levels in a high-rise apartment. Health Phys 61:263–265 (1991).

24. Chittaporn P, Harley NH. A five-year data base of outdoor radon. Health Phys 68(suppl 6):S89 (1995).

25. Fissene IM, Keller HW. Continuous indoor and outdoor measurements of ^{222}Rn in New York City: city as a source. Environ Int 22(suppl 1):S131–S138 (1996).

26. Doi M, Kobayashi S. Vertical distribution of outdoor radon and thoron in Japan using a new discriminative dosimeter. Health Phys 67:385–392 (1994).

27. Porstendorfer J. Properties and behaviour of radon and thoron and their decay products in the air. J Aerosol Sci 25:219–263 (1994).

28. Put LW, de Meijer RJ. Variation of time-averaged indoor and outdoor radon concentrations with time, location, and sampling height. Radiat Prot Dosim 24:317–320 (1988).

29. U.S. Geological Survey. Surface equivalent uranium (eU) concentrations from the NURE [National Uranium Resource Evaluation]. Available: http://sedwww.cr.usgs.gov:8080/radon/DDS-9.html [cited 11 December 1998].

30. Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory. County averaged NURE [National Uranium Resource Evaluation] eU data from the high radon project. Available: http://eande.lbl.gov/IEP/high-radon/files.html [cited 11 December 1998].

31. Wasiolek PT, James AC. Outdoor radon dose conversion coefficient in south-western and south-eastern United States. Radiat Prot Dosim 59:269–278 (1995).

32. Wasiolek PT, Schery SD. Outdoor radon exposure and doses in Socorro, New Mexico. Radiat Prot Dosim 46:49–54 (1993).

33. Wasiolek PT, Schery SD, Broestl JE, James AC. Experimental and modeling studies of ^{220}Rn decay products in outdoor air near the ground surface. Environ Int 22(suppl 1):S193–S203 (1996).

34. Schery SD, Wang R, Eack K, Whittlestone S. New models for radon progeny near the earth's surface. Radiat Prot Dosim 45:343–347 (1992).

35. Field RW, Smith BJ, Brus CP, Lynch CF, Neuberger JS, Steck DJ. Retrospective temporal and spatial mobility of adult Iowa women. Risk Anal 18:575–584 (1998).

36. Alavanja MCR, Brownson RC, Lubin JH, Berger E, Chang J, Boice JD Jr. Residential radon and lung cancer among non-smoking women. J Natl Cancer Inst 86:1829–1837 (1994).

37. Letourneau EG, Krewski D, Choi NW, Goddard MJ, McGregor RG, Zielinski JM, Du J. Case–control study of residential radon and lung cancer in Winnepeg, Manitoba, Canada. Am J Epidemiol 140:310–322 (1994).