RESULTS FROM A PILOT STUDY TO COMPARE RESIDENTIAL RADON CONCENTRATIONS WITH OCCUPANT EXPOSURES USING PERSONAL MONITORING

by: B. R. Litt
New Jersey Dept. of Environmental Protection
Division of Science and Research, CN-409
Trenton, New Jersey 08625

J. M. Waldman
Dept. of Environmental and Community Medicine
Robert Wood Johnson Medical School, UMDNJ
675 Hoes Lane
Piscataway, New Jersey 08854

N. H. Harley and P. Chittaporn
Dept. of Environmental Medicine
New York University Medical Center
550 1st Ave.
New York, New York 10016

ABSTRACT

Radon concentrations in indoor air are usually measured for a few days to months in one or two locations in a home. This approach can lead to errors when estimating occupant exposures. We investigated whether occupant exposures to radon could be better determined by person-based measurements than by stationary home measurements.

A pilot study was conducted in 6 homes with elevated radon levels. Occupants wore personal radon monitors (PRMs), developed for use in this research. Using room occupancy and activity diaries, personal exposures were compared with measurements from stationary monitors. Stationary measurements included identical PRMs placed in many rooms of the home, as well as the occupant's workplace; continuous radon measurements in the principal activity room; and continuous progeny measurements in at least two locations per house. Studies were conducted for one-week periods in winter, with 2 homes also studied in summer. PRM validation and pilot study results are presented.

INTRODUCTION

Since 1985, many measurements of radon-222 concentrations in indoor air have been made throughout the USA. Many have been made by private citizens, to determine whether they should remediate their homes. Others have been made by government agencies, to assess the magnitude and distribution of the public health threat posed by radon (1). Measurements are usually made with integrating detectors over several days to months in one or two locations in a home. A simple, yet widely accepted, model is that such measurements accurately estimate inhabitant exposures. Until the present study, however, this model had not been tested using actual measurements of person-based exposures. Accurate exposure estimates are necessary to understand better the health risks associated with measured concentrations of radon.

Indoor radon concentrations can exhibit major spatial and temporal variability. The temporal variations occur both on long (seasonal) and short (hours or days) timescales (2). In different zones of a single house, concentrations differing by factors of 2-3 are routinely seen, and factors of 10 can be encountered (3). In addition, people are mobile both in space and time, within and outside their homes. For these reasons, it is likely that an inhabitant's exposure may differ significantly from exposure to a time-integrating detector placed in a single location.

This pilot-scale study investigates personal exposures to radon in the home using fixed and portable (person-based) monitors. A personal radon monitor used in this work is validated. The relationship between stationary radon and radon progeny measurements and occupant exposures to radon gas has been studied. Simple models for personal radon exposure are tested. The project has provided data needed to assess the utility of personal radon monitoring in a residential setting.

EXPERIMENTAL DESIGN

Homes studied were known to have elevated radon levels (i.e., greater than 300 Bq/m^3 (8 pCi/L) in living areas as determined by New Jersey Department of Environmental Protection's (NJDEP) Radon Confirmatory Monitoring Program 3-day charcoal canister measurement). Elevated levels were desirable to ensure that there was measurable radon exposure without requiring long measurement periods. In addition, homes had at least two occupants willing to wear the personal monitors. While study participants were not statistically selected, an attempt was made to include people of different lifestyles. It turned out that all homes studied had basements, none of which were regularly occupied as living space.

Studies were conducted for one-week periods. In winter of 1989 to 1990, six homes (Houses A through F) were studied, with a total of 13 occupants. Of the six, four households dropped out of the study after the winter measurements, to seek radon mitigation. Houses B and F were revisited the following summer, with a total of three occupants restudied. House A has been excluded from this data analysis because an earlier version of the PRM was used, which did not have sufficient precision for the relatively low exposures to be measured in this study. Before studying Houses B-F, modifications were made to the PRM which substantially improved precision.

Study participants wore PRMs everywhere throughout the study, except into the shower or in bed, where they placed the PRMs nearby. Coincidental stationary radon and radon progeny measurements were made in various zones of the home and the occupant's workplace. The type, duration and location of the measurements are shown for a prototypical house in Fig. 1.

Participants completed activity diaries each day, recalling where they went and what they did over the past 24 hours. In addition to location, the activity diary chronicled heating and ventilation, appliance use, smoking (active and passive) and the presence of guests in the home. The activity diary also asked whether the person had forgotten to wear the PRM that day, and if so, when, where, and for how long.

The stationary and person-based PRMs were exposed for 2-day periods and then exchanged for fresh PRMs. This was done for a total of three exposure periods. In this way, the measurements were repeated several times for each house. In House A unequal periods of 1, 2, and 4 days were used, because the optimum period was not known. Subsequent homes used repeated 2-day exposures. The exposure periods usually began in the evening, because that was most convenient for participants. The middle exposure period ran from Friday evening to Sunday evening, representing weekend behavior for participants who had normal work schedules. The other two periods represented the weekday routine.

The study participants were sent the results of the stationary measurements made in their homes. In addition, they were sent a follow-up questionnaire to evaluate many aspects of the study. In general, people found study participation interesting and not too intrusive. However, people were unanimous in wanting a smaller, less obtrusive PRM.

METHODS

The sensitive, passive, integrating personal radon monitor (PRM) has been developed specifically for use in this project (4)[1]. Radon diffuses into the monitor through a conducting foam barrier which keeps out the progeny. The radon detector is CR-39[2], a solid state nuclear track film. Gamma ray exposure data are obtained from CaF_2 thermoluminescent chips[3] (TLD) placed beneath the CR-39. The CR-39 and CaF_2 TLD are covered with thin aluminized Mylar which nullifies any charge artifacts. Each monitor has provision for triplicate CR-39 film and TLD exposures. Duplicate films and TLDs were used for this project. Only the radon measurements are discussed in this paper. Made of lightweight conducting plastic, the version of the PRM housing used in this research is a cylinder, 7.5 cm in diameter and 3.0 cm in height. It is designed to be worn on a belt. The PRM is shown in Fig. 2. Extensive chamber studies and calibrations have been performed on the PRM. As a quality control measure, in addition to the internal duplicates, all PRM measurements in this pilot study were also made in duplicate. Occasionally larger numbers of replicate exposures were done. Results of the PRM performance assessment work are presented below.

Trip blanks accompanied the PRMs and any exposure gained during transit was subtracted. This was necessary because the PRMs were active from the time they left the laboratory to the time they returned. For the periods used in this study, the trip blanks had an average of 8 tracks, compared with 4 tracks for the laboratory blanks.

To minimize transit/storage exposures, PRMs were sent to and from the laboratory using overnight mail. If short term storage was necessary, PRMs were kept in a "low radon area" (a car trunk). The transit/storage exposure subtraction was especially important for low radon exposures (such as those obtained in a subject's workplace) and for the gamma ray exposure measurements. Because the study was done in homes with elevated radon levels, the transit/storage exposures were typically a small fraction of the overall exposures. The exposures reported here are those received by the subjects or by stationary PRMs in their locations of interest.

A variety of techniques were used to make the stationary measurements. PRMs were used in a stationary mode to make 2-day integrating measurements. Continuous (hourly average) radon measurements were made with Pylon Model AB-5 radiation monitors equipped with passive radon detectors. Continuous progeny measurements were made with Eberline continuous working level monitors. In addition to PRMs, charcoal canisters were used to make integrated radon measurements, due to their widespread use for this application. Charcoal canisters were placed at least one meter from PRMs and other passive radon

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[1]Patent application filed.

[2]Obtained from TechOps/Landauer in batch quantities pre-cut for this detector.

[3]Obtained from Harshaw/Filtrol Partnership, Cleveland, OH.

RESULTS

EXPOSURE RESULTS

The person-based exposure measurements (E_{mp}) are compared with stationary measurements in several ways. First, the measured exposures, in Bq m^{-3} h, are compared with the exposures an occupant spending all the time in the basement, or in the living area would receive. The average basement exposure (E_{m0}) is understood to be a gross approximation to exposure, but is nevertheless used by some policymakers and homeowners to estimate occupant exposures. The average living area exposure (E_{m1}) or the average sleeping area exposure (E_{m2}) would be expected to better approximate occupant exposures. The measured exposures for each participant are also compared with exposures calculated according to the model (E_{cp}),

$$E_{cp}=\sum_i Rn_i T_i + Rn_w T_w + Rn_b T_{out}$$

where Rn_i is the average radon concentration in the ith zone of the home, Rn_w is the average radon concentration at work, $T_{i,w}$ is the time spent in a zone or at work, Rn_b is the background, or outdoor radon, and T_{out} is the time spent not in a monitored area (for example, outdoors, in transit, or shopping). The value of Rn_b is determined from the difference in trip and laboratory blanks and is typically 7 Bq m^{-3} (0.2 pCi L^{-1}). For all the winter and most summer measurements, this last term is negligible compared with the other exposure terms.

The comparisons of E_{mp} with the various exposure estimates are shown in Figures 4-7. The lines in these figures are linear regression lines, without intercepts. The slopes and coefficients of determination are given in the figure captions. Fits were significantly better without intercepts than with them.

TABLE 1. AVERAGE RATIOS OF MEASURED PERSONAL EXPOSURES TO BASEMENT, LIVING AREA, BEDROOM AND CALCULATED PERSONAL EXPOSURES

Season	N	$E_{mp}:E_{m0}$	$E_{mp}:E_{m1}$	$E_{mp}:E_{m2}$	$E_{mp}:E_{cp}$
Winter	33	0.30±0.04[a]	0.80±0.10[a]	0.72±0.10[a]	1.17±0.18[a]
Summer	9	0.42±0.17	0.74±0.30	1.05±0.44	1.30±0.62
Combined	42	0.33±0.05	0.78±0.10	0.80±0.12	1.20±0.20
Combined[b]	42	0.19±0.02	0.60±0.10	0.59±0.08	1.03±0.16
Combined[c]	42	0.26±0.05	0.86±0.18	0.70±0.08	1.18±0.13

[a] 95% confidence limit.
[b] Numbers given are weighted averages.
[c] Numbers given are unweighted linear regression coefficients with E_{mp} the dependent variable.

The average ratios of E_{mp} to these parameters are summarized in Table 1. Weighted averages were also calculated (the weighting was derived by propagating the counting errors for each datum). This was done to investigate whether the few higher exposures would unduly influence the conclusions. The weighting does make a difference, albeit not a large one, in the ratios. From Table 1, we conclude that a typical study participant received 60% of the radon exposure that a stationary monitor placed in the living space received. As indicated by the good correspondence of E_{mp} to E_{cp}, people who spent less time at home, or less time in high radon areas of the home, received less exposure. Winter and summer results appear to have differences, but

measurement equipment. A hygrothermograph placed in the basement recorded the temperature and humidity throughout the study period.

Integrating 6-day radon measurements were made in the workplaces of participants employed outside the home. A pair of stationary PRMs was sent to work on the first day of the study, and brought home on the last day.

PRM CHARACTERISTICS AND VALIDATION

CHARACTERISTICS

As part of the development of the PRM, extensive studies were done in the radon chamber of the USDOE's Environmental Measurements Laboratory (4). Calibrations verified that the response of the detector is linear in the exposure range of interest. The calibration factor obtained was 2.6 tracks (kBq m^{-3} h)$^{-1}$, or 2.3 tracks (pCi L^{-1} d)$^{-1}$. Subsequently, the PRM was entered in the 1990 USDOE radon intercomparison. The result, based on the average of 4 monitors, was $98 \pm 3\%$ of the "true" value.

Two other PRM properties that were characterized are the diffusion time of radon into the PRM chamber and the effect of a moving air stream on the calibration factor. The diffusion of radon into the PRM chamber was studied. The half-time for radon diffusion was determined to be approximately 4 minutes. This is a desirable diffusion time, as it is short enough to allow exposures due to relatively short times spent in high radon areas to be registered, but it is not so short as to allow for significant signal from any thoron gas that might be present.

The moving air stream effect was studied by placing PRMs in the radon chamber in front of a fan. At a face velocity of 3.7 km h^{-1} the calibration factor doubled. This velocity might be attained by brisk walkers. The moving air stream effect was not expected to make a significant contribution to the exposure measurements. The exposure data were examined for the presence of systematic errors that could arise from this moving air stream effect. Any such errors that might have been present were not detectable.

FIELD VALIDATION

The comparisons of stationary PRM exposures with co-located continuous radon measurements and charcoal canister measurements are shown in Fig. 3. The dashed line is a guide to the eye, of slope 1, through the origin. The agreement is quite good in the lower exposure range. Discrepancies in the higher exposure range can be explained by experimental errors, specifically in the calibration factors, especially since the continuous measurements are consistently higher than the PRM and the charcoal canisters are consistently lower.

We expected the precision of the PRM measurements to be governed by counting error in the relatively low exposure region encountered in this study. To investigate this hypothesis, the relative standard deviations of the stationary and person-based replicate measurements versus radon exposure (in units of mean tracks) have been studied. Analysis indicates that the distribution of observed relative standard deviations is consistent with what is expected due to counting error. We thus conclude that, in the exposure range of interest, the PRM precision is limited by counting error.

To directly verify the accuracy of the person-based PRM measurements it would be ideal to have people wear PRMs for a known time in a known radon environment, such as a chamber. Such tests have not been done in this work, for practical and ethical reasons. Instead, the person-based exposure measurements (E_{mp}) were compared with the expected exposures (E_{cp}). The expected exposures were calculated from the stationary measurements and from the occupancy data reported in the activity diaries. This analysis and its results are discussed in detail in the next section. From this analysis we conclude that if a bias is present (due to the moving air stream effect, or from other sources) it is small.

the small sample size and low summer exposures obscure the causes, if any, of these differences. One obvious source of winter/summer differences is participants leaving their monitors at home, as reported.

CONTINUOUS MONITORING RESULTS

The continuous radon and radon progeny data are being examined both qualitatively and quantitatively. The data have been examined qualitatively in two ways. First, effects that could be correlated with human activities were sought. For the radon data, occupant's records of ventilation were compared with the occurrence of any radon peaks or troughs. For the progeny data, the coincidence of changes in the equilibrium ratio with occupant activities (for example, ventilation, cleaning, and smoking) was investigated. Second, any major time-variations in radon concentration taking place in the presence of occupants were noted. The quantitative analysis applies standard statistical methods to obtain information on the time-variation of radon and radon progeny in the study houses. Results are not ready to report at this time, but may be available by April.

DISCUSSION AND CONCLUSIONS

The sample size in this pilot study is far too small to draw conclusions that are representative of the general housing stock, or of the general population. Nevertheless, some patterns are clear here, and probably can be generalized. This is particularly true when these patterns confirm what is expected from "common sense".

One important pattern is the good agreement of measured occupant exposures with expected exposures. This tends to confirm that 1) the exposure model commonly used is correct, 2) the PRMs and study participants performed well and 3) the most significant source of indoor radon exposure is the home. Another pattern is that measurments made in basements that are not regularly occupied consistently overestimate occupant exposures. The degree of this overestimation is dependent on the distribution of radon within the house and how much time is spent at home. Measurements made in sleeping areas and living areas correlate better with and overestimate by less occupant exposures than the comparable basement measurements.

There are a number of directions in which future research using the PRMs could be directed. First, it would be desirable to have a smaller version of the PRM, so that it could be worn for longer periods without distraction or discomfort. It should be possible to make a much smaller version without sacrificing sensitivity.

Once this is accomplished, the PRM could be used in a much larger, simpler population-based exposure assessment. This could simply compare person-based exposures to stationary exposures. Activity diaries and continuous measurements could be done in a subset of homes for quality assurance purposes. Because the PRM could be worn for a longer time, it would not be necessary to study occupants of homes with elevated radon levels. Data gathered in such a study could contribute to the ongoing efforts of epidemiologists to better understand the health threat posed by indoor radon.

Another area in which the PRM may be of use is in characterizing the nature of occupant exposure to radon arising from sources other than soil gas. In the U. S., this would mainly be domestic well water. Occupants of homes with elevated radon in water, in which soil gas is not a significant radon source could be studied. In combination with other monitoring techniques, actual human exposure could be determined, as distinct from the average contribution of radon in water concentrations to radon in air concentrations.

ACKNOWLEDGEMENTS

The contributions of many individuals and organizations to this work are gratefully acknowledged: the New Jersey families who participated, NJDEP's Division of Science and Research, NJDEP's Radon Section, Princeton University's Center for Energy and Environmental Studies USDOE's Environmental Measurements Laboratory, S. C. Scarpitta, N. Freeman, and E. Wong. Major funding for this work was provided by the New Jersey State Commission on Cancer Research, grant #88-602-CCR-00 and NJDEP DSR contract #P50587.

The work described in this paper was not funded by the U.S Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

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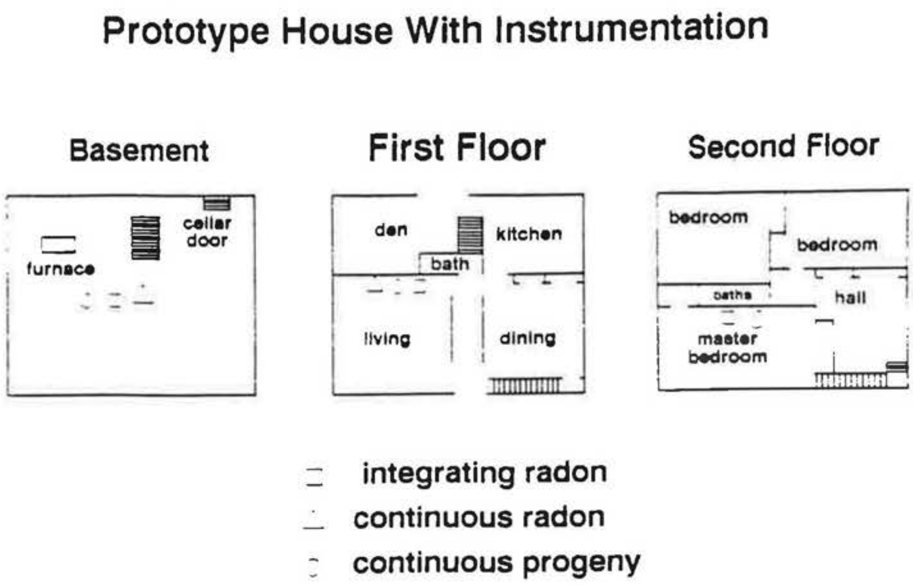

Figure 1. Prototypical study home, showing locations of stationary radon and radon progeny measurements.

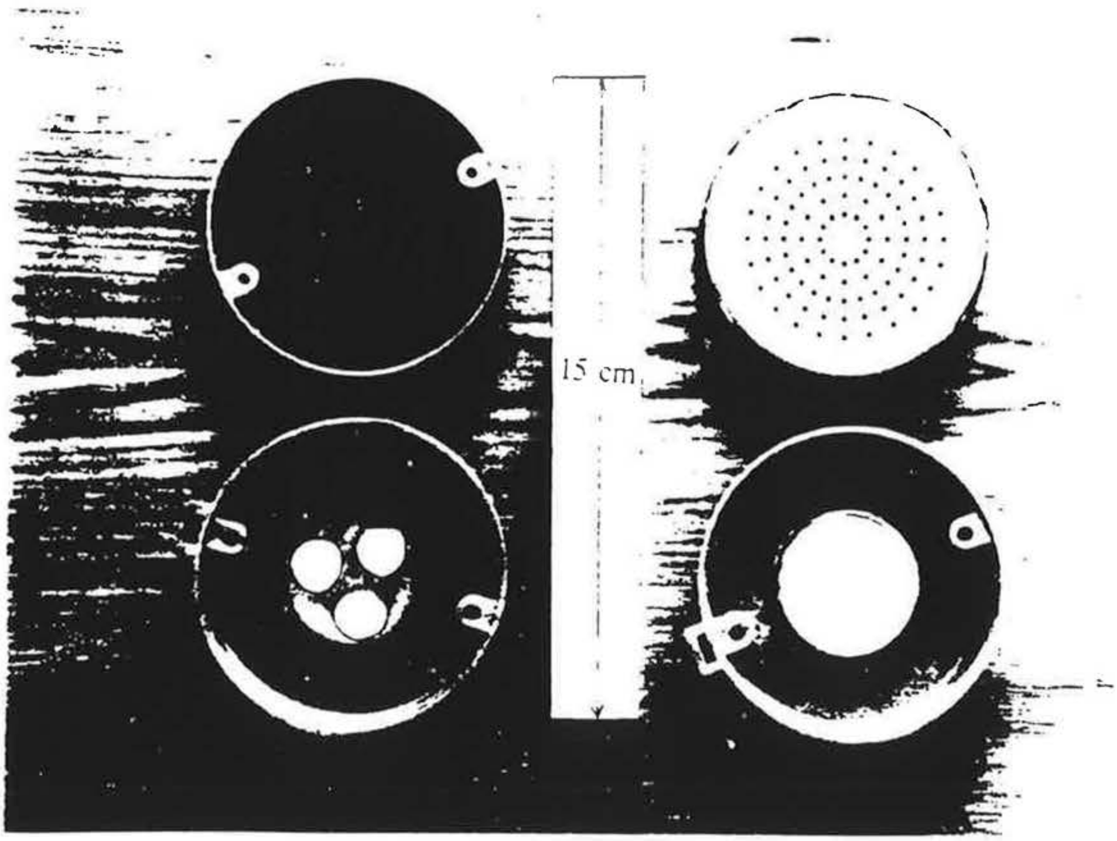

Figure 2. Photograph of the Personal Radon Monitor (PRM). Top left: inside of the PRM top, with conducting foam. Bottom left: PRM bottom, with three wells that hold the round TLD chips and square CR-39 films. Top right: outside of PRM top. Bottom right: aluminized Mylar covering the detectors.

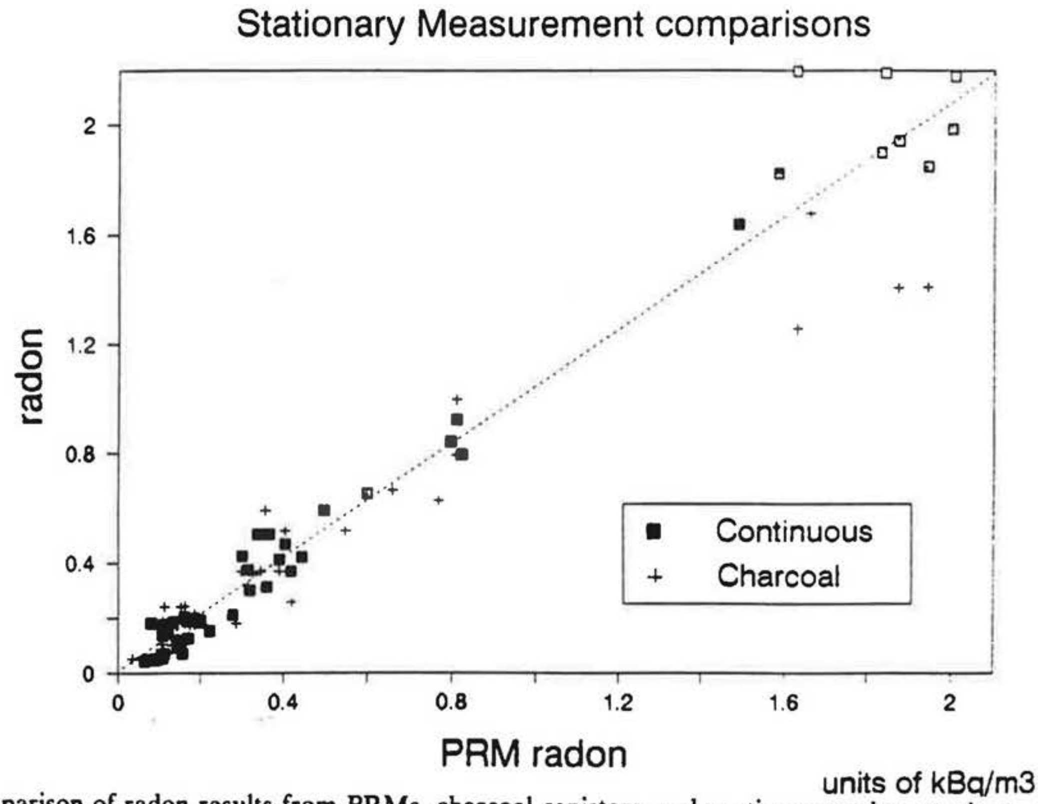

Figure 3. Comparison of radon results from PRMs, charcoal canisters, and continuous radon monitors.

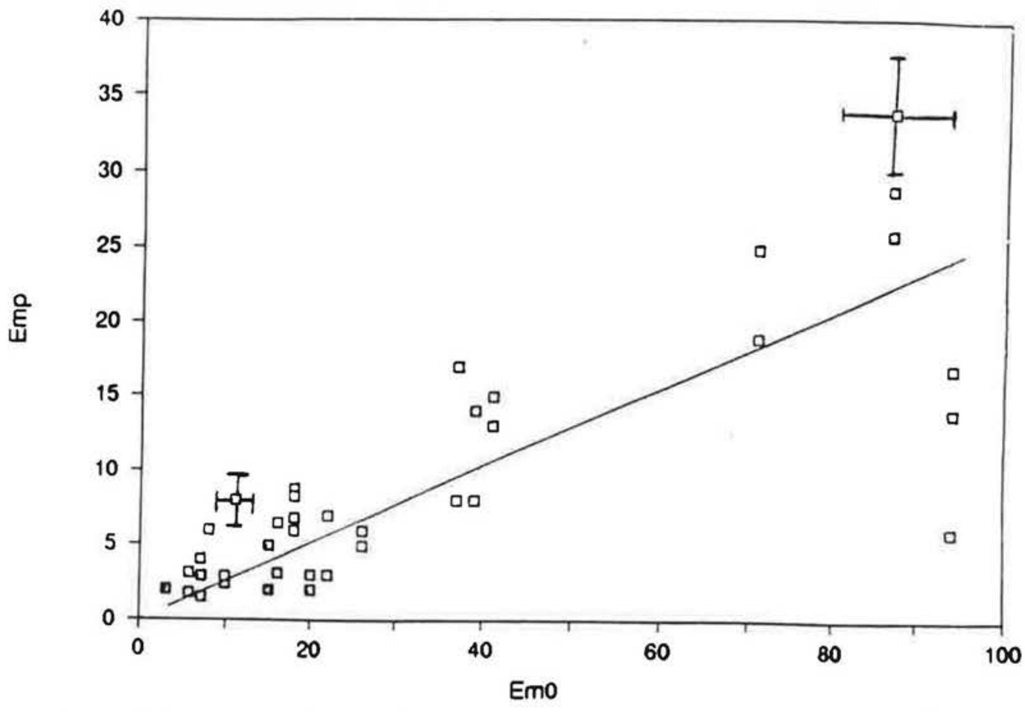

Figure 4. Comparison of the measured person-based exposures versus measured basement exposures. Slope = 0.26, r^2 = 0.65. Sample error bars (1 standard deviation counting error) are indicated for two data points.

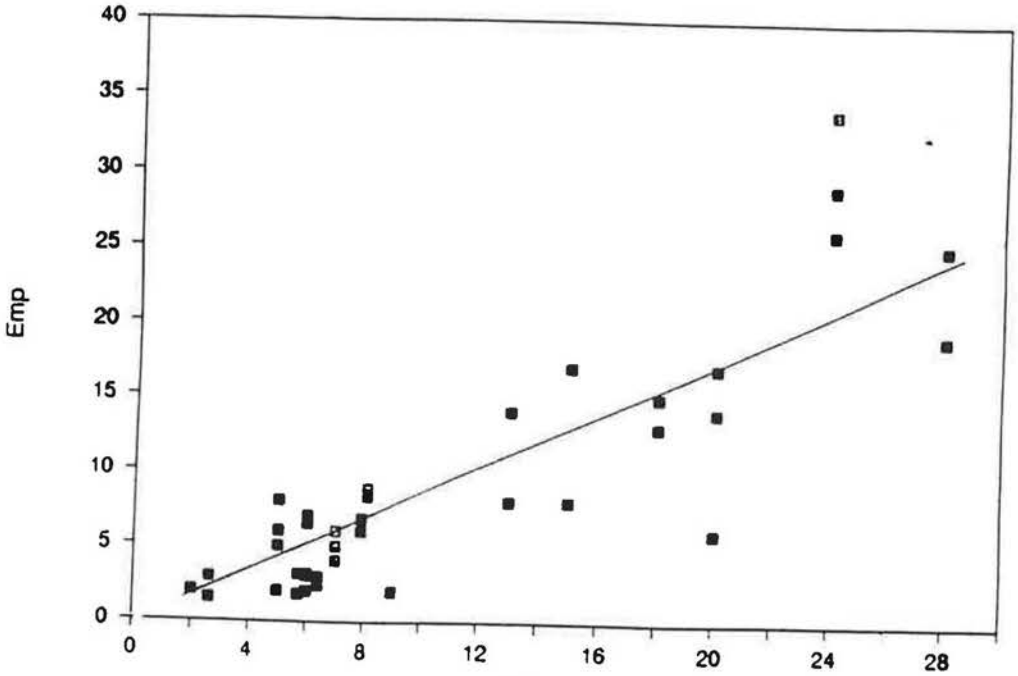

Figure 5. Comparison of the measured person-based exposures versus measured living area exposures. Slope = 0.86, r^2 = 0.77.

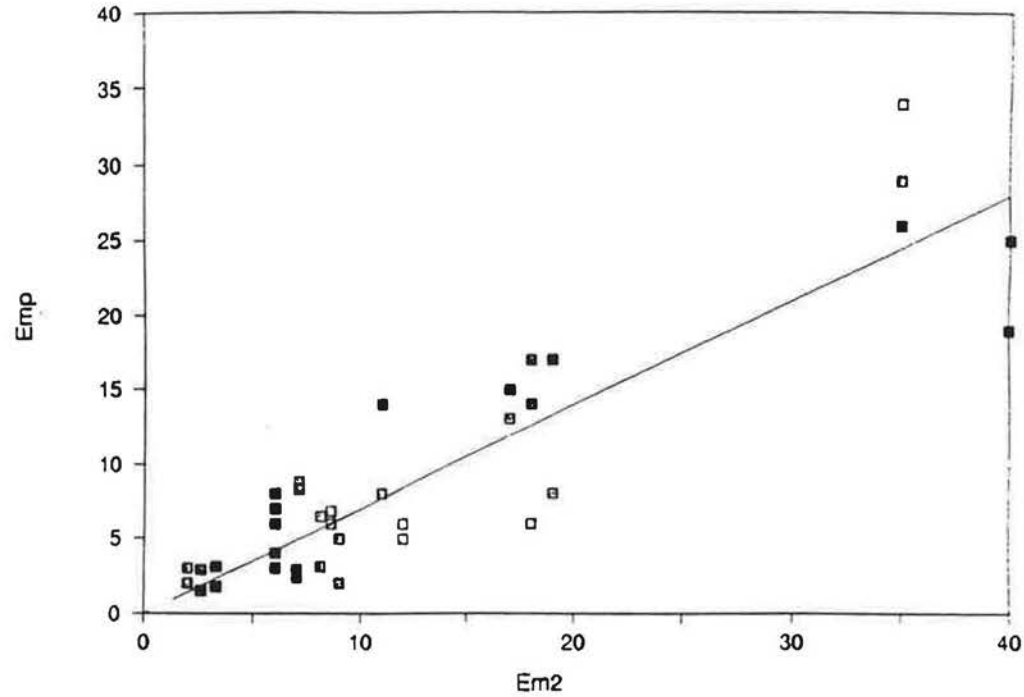

Figure 6. Comparison of the measured person-based exposures versus measured bedroom exposures. Slope = 0.70, r^2 = 0.84.

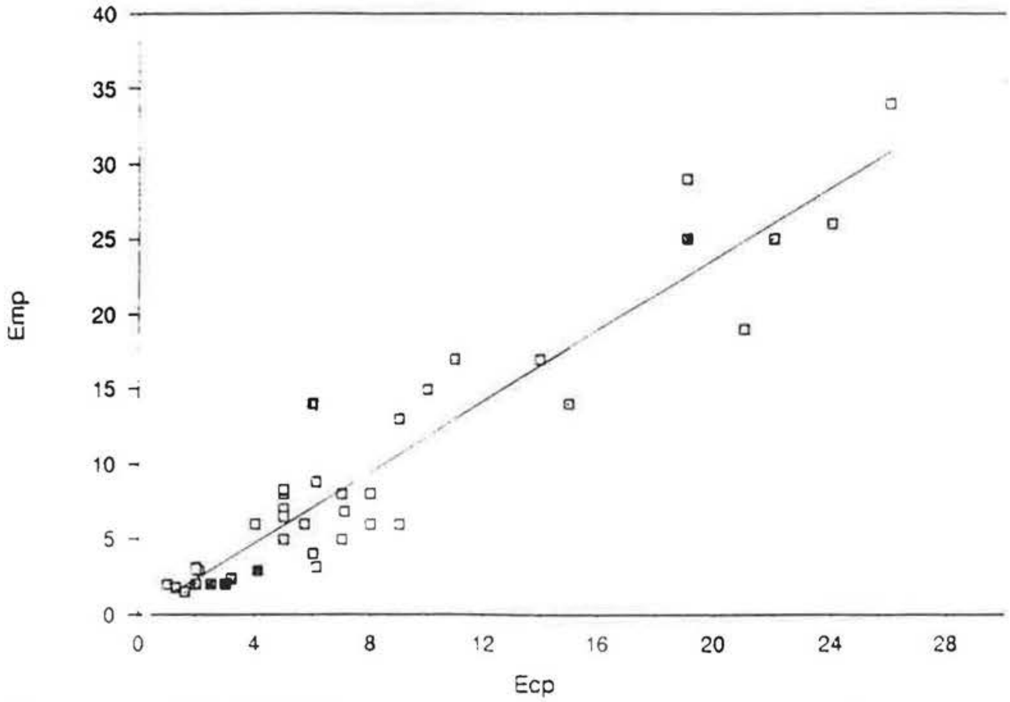

Figure 7. Comparison of the measured versus calculated person-based exposures. Slope = 1.18, r^2 = 0.90.