The Impact of Occupancy Patterns on the Assessment of the Value of Domestic Radon Remediation Programmes in the UK

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INTRODUCTION

Radon gas has a variable occurrence in the natural environment, and has been shown to cause lung cancer when present in excessive amounts in mines (1). Recently, it has been reported that levels found in domestic housing can be sufficiently high to be a significant risk to occupants (2)(3). It is possible to reduce radon levels in houses and so programmes to identify and remediate such houses in order to reduce the risk to occupants can be justified.

In the UK, the National Radiological Protection Board (NRPB) has defined radon Affected Areas as those having at least 1 % of housing above the Action Level of 200 Bq m^{-3} (4). The county of Northamptonshire is one of these areas with 6.3 % of houses above the Action Level (5).The costs and benefits of remediation of domestic properties in Northamptonshire have been studied (6), and found to be similar to theoretical predictions, and justifiable when compared to other radiation dose reduction programmes, and other health interventions (7).

One key assumption when calculating the initial risk and any benefit from remediation is the time spent by each occupant within the home. Denman and Phillips (6) assumed 50 % occupancy to eliminate any exposure at the workplace, or whilst out of the home. However, the BEIR VI report, in contrast, assumed 70 % occupancy (8). The National Radiological Protection Board (NRPB), had previously assumed that average occupancy in the UK was around 80 % (9), and this latter figure was assumed by Kennedy et al, 1999 (7). This paper presents new occupancy data for Northampton and the surrounding county, and considers its significance for evaluating the effects of remediation programmes.

METHODS

Data on indoor occupancy were collected during surveys of time activity and journey patterns of three target groups (adult residents, College students and schoolchildren) in the northern suburbs of Northampton, as part of an EPSRC-funded study of road traffic and outdoor air pollution. Surveys were conducted using a combination of telephone interview and questionnaire methods. Adult residents from seven electoral wards in the Kingsthorpe area of Northampton were selected at random from the telephone directory and were telephoned in the early evening, when a pilot survey had indicated that occupancy was at its peak. A scripted questionnaire, asking about the respondent's activity in the last 24 hours, was conducted during the call. Questions related to the time spent indoors at home, and at other locations, and travel time. If the named individual was not at home, an appointment was made to ring back. If two further attempts at contact were unsuccessful, another adult occupant was invited to answer the questions. The survey was conducted in December 1997, and usable data from 286 respondents were obtained.

College students and schoolchildren were surveyed during October and November 1998, using written questionnaires and a simple time-activity diary, designed to seek information on their activity in the previous 24 hours. 992 questionnaires were distributed to second year undergraduates at University College Northampton through the teaching staff; of the replies, 247 were from students resident in the study area and contained usable data. The survey of school-children covered children aged 9 to 12 years old, who lived and went to school within the study area were surveyed. A simple time-activity diary, and accompanying questionnaire, were used to obtain information on the child's whereabouts and travel patterns during the previous 24 hours. To ensure accuracy, the questionnaire and diary were completed on three separate occasions during the day - twice at school, supervised by a teacher, and once in the evening, supervised by a parent. From an initial total of 1037 questionnaires distributed, from which 902 were returned. From these 700 children were found to live within the study area, out of which full and usable responses were obtained from 332 children.

In addition, in early 1999, written postal questionnaires were sent to two further sub-groups within the county. The first group comprised of a random sample of 1000 households were chosen by the NRPB, out of 5593 Northamptonshire households who were known to the NRPB as having radon levels above the Action Level. Questionnaires were despatched by the NRPB to the sample of 1000 households and were returned to one of the authors (CK). The second sub-group was a random sample of 12 households out of the 62 who formed the contractor remediated sample discussed elsewhere by Denman and Phillips, 1998 (6); and Kennedy et al, 1999 (7).

RESULTS

Results of the telephone survey of adults in suburban Northampton are shown in Figure 1. A trimodal distribution of home occupancy can be seen, with peaks at 14 hours (58 % of the day), 22 hours (88 %) and 24 hours (100 %). The average occupancy for the whole sample was 17 hours 17 minutes (72 %). Interestingly, this distribution shows a complete range of occupancy, from 0 to 24 hours, with a group who leave the home for less than 2 hours each day, and another (10.5 % of the sample) who do not go out at all.

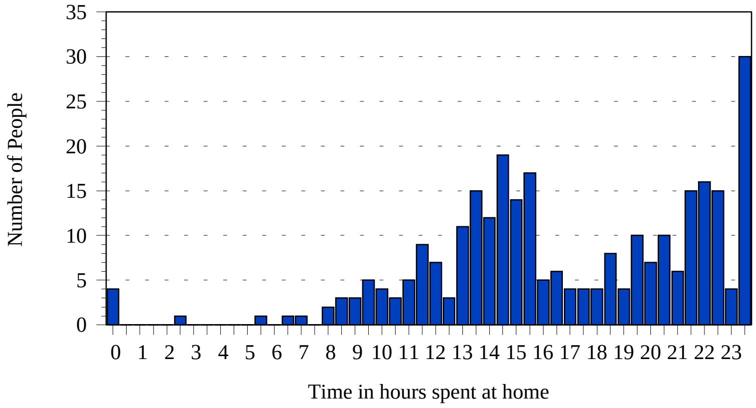

Figure 1 - Hours per day spent at home - Adults in Northampton

Home occupancy of schoolchildren was far more consistent, though with a strong negative skew, as shown in Figure 2. Occupancy levels ranged from a minimum of 8 hours (33.3 %) to a maximum of 17 hours 10 minutes (71.5 %). Average occupancy was 14 hours 25 minutes (60 %), and the distribution showed a marked mode at 16 hours 30 minutes (68.8%). The results also showed that the group spent at least 20.14 % (4 hours 50 minutes) in school.

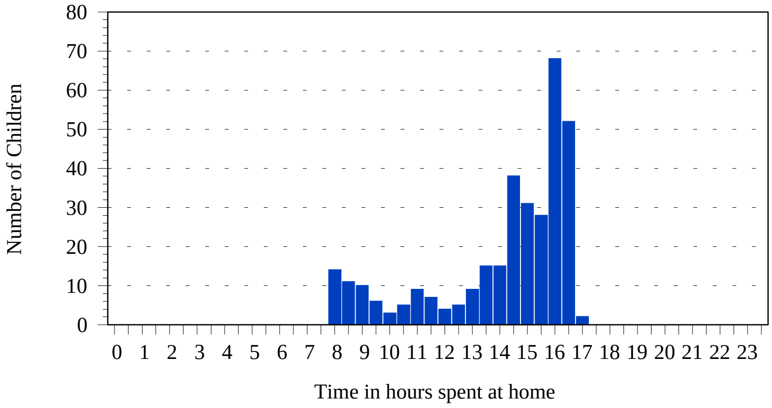

Figure 2 - Hours per day spent at home - School-children in Northampton

The more specific time activity data available for students in Northampton allowed occupancy patterns to be explored in a more detailed manner (Figure 3). The majority of students spend most of their time either at home or in other indoor environments. As is to be expected, occupancy patterns vary markedly across the day. Home occupation remains high (with over 90% of students at home) between about 1 am and 7 am. During College hours, only 20-30% of students were at home, compared to 50% at College and 20-30% elsewhere. After 5 pm, home occupancy again rises, with around 60-70% of students at home. Other indoor locations also increase during the evening, peaking at about 30% between 8 and 10 pm.

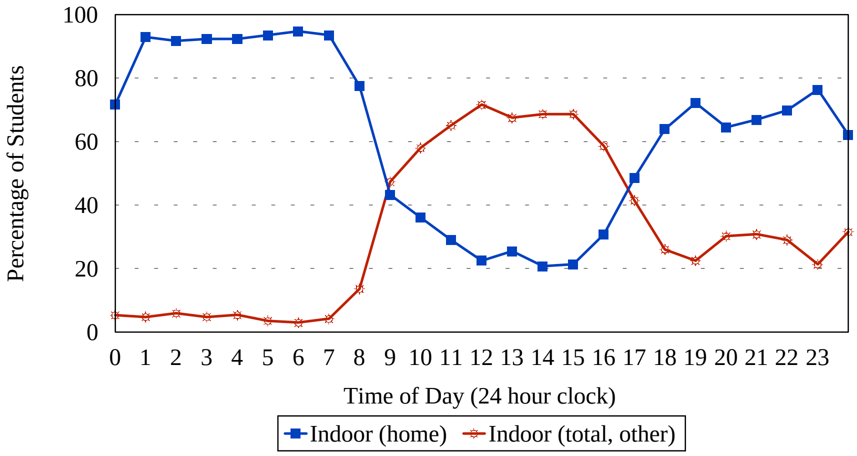

Figure 3 - Percentage of students indoors throughout the day

Results from the survey of 1000 adults from households in Northamptonshire (based on the postal survey) are shown in Figure 4. Out of the 1000 postal questionnaires, 469 were returned, but of these only 301 had recorded answers about occupancy. Based on these, the occupancy distribution is seen to be highly varied, with a range from 3 hours to 24 hours, and peaks at 12, 16, 18 and 20 hours. Average home occupancy for the whole sample was 16 hours 15 minutes (67.7 %). This compares with an average of 18 hours 10 minutes (75.7 %) for the twelve people surveyed from remediated homes.

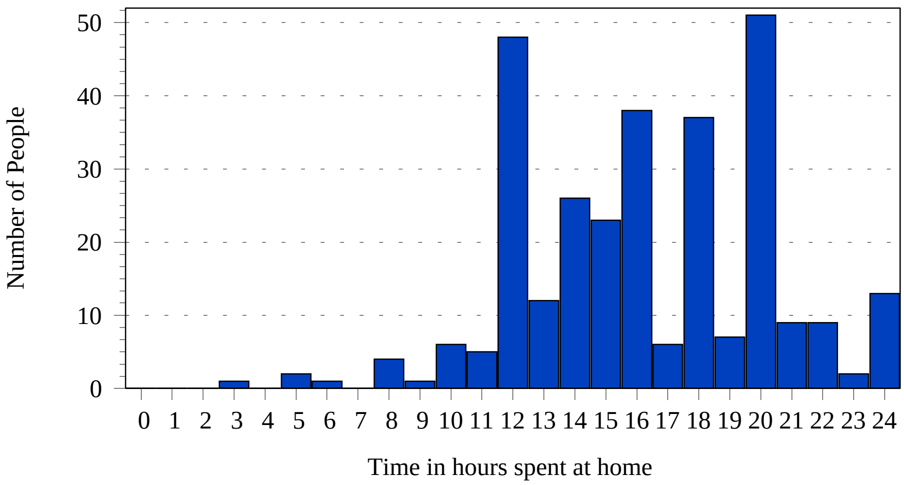

Figure 4 - Hours per day spent in the home
- Postal questionnaire of Adults in Northamptonshire

DISCUSSION

Radon gas is concentrated in buildings and is quickly dispersed in the outdoor environment; the radiation dose received by occupants depends not only on the average indoor radon level, but also on the time spent indoors. In assessing the risk from radon, the National Radiological Protection Board took the average home occupancy of 80 %. This was derived by work by Francis (10), where the principal source of information was a British Broadcasting Corporation (BBC) survey of 1974 (11). Francis found the average annual residential occupancy was 67 % for men, 76 % for women, 88 % for housewives and 75 % for the all adults.

Francis also reported the percentage of the surveyed group at home at various times of the day; Table 1 summarises these data and compares them to our results from College students. The results show that a far higher percentage of students were out of the home during the day compared with the total population sampled by the BBC. Housewives showed the highest occupancy rates at all times of the day. During the evening, the percentage of students in other indoor locations (i.e. not the home) was almost twice that of the average adult population.

	01:00 AM	12:00 Noon	20:00 PM	Survey Date
BBC				
Housewives	99 %	78 %	81 %	1974
All Adults	99 %	57 %	80 %	1974
Northampton				
Students	95 %	22 %	65 %	February 1998

Table 1 - Percentage of people at home at various times through the day

Average home occupancy levels for the various sample populations considered here vary from 14 hours 25 minutes for schoolchildren, to 16 hours 15 minutes for the adults sampled in the postal survey and to 17 hours 17 minutes for the adults sampled in Northampton. Average values, however, tell only part of the story. As comparison of Figures 1 and 2 and interpretation of Figure 3 show, marked differences occur in the distributions of home occupancy of the three groups (schoolchildren, students and housewives) sampled in Northampton. The adult populations sampled both in Northampton, and more widely by the postal survey also show strong polymodal distributions with large ranges. For example, there is a group consisting of those in full time employment or school who are at home for around 14 hours each day, a group who only go out for around 2 hours each day, which may include housewives and the elderly, and another group who do not go out at all. This latter group may include people such as the elderly infirm, the handicapped, and Asian wives in *purdah* - a group previously identified by Denman et al (12) as showing a very specific time activity pattern. Together, the results thus suggest that the population as a whole is highly heterogeneous in terms of its home occupancy patterns, both between different demographic groups, and within any one group.

	This Study	**BBC**	**Iowa (13)**	**California (14)**	**Dörre (15)**	**Tung (16)**
Country	**UK**	**UK**	**USA**	**USA**	**Germany**	**China**
Toddlers				73 %	66.2 %	
Schoolchildren	60 %			62 %		44.8 %
Students					66 %	60.5 %
All Adults	72 %	75 %		61.9 %		
All Elderly				74 %		81.8 %
Women		75 %	72.1 %			
Housewives		88 %				71 %
Age 20, Female, 3 children			71 %			
Age 50 Female, no children			63.2 %			
Age 80, female			75.2 %			
Men		67 %				53.2 %

Table 2 - Comparison of Average Percentage Occupancy in the Home in various Countries

Results from this study can also be compared with data from other studies of time activity in other countries (Table 2). The Iowa Radon Lung Cancer Study obtained data for 619 females who occupied the same house for at least 20 years (13). Occupancy was seen to vary with age and number of children, with average occupancy as low as 63.2% for 50 year old women with no children, rising to 71 % for 20 year olds with three children, and 75.2 % for 80 year old women. Other studies in a variety of countries have shown a similar patterns, with the young and old spending more time in the home than students and young adults. The results are summarised in Table 2, and are remarkably similar across a number of industrialised countries, although occupancy can be much lower in warmer countries, such as Pakistan, where average adult occupancy was found to be 30 % (17).

The choice of occupancy level has significant implications for the assessment of radon risk and for analyses of the effects of radon mitigation strategies. These implications can be illustrated by reference to the remediated homes in Northamptonshire first reported by Denman and Phillips (6). 65 remediated homes have now been studied. Based on radon monitoring in these homes, the collective dose reduction from remediation can be estimated as 2.22 man-sieverts at an occupancy rate of 50%. If the NRPB assumption of 80% occupancy is applied, in contrast, the dose reduction rises to 3.55 man-sievert. For an occupancy of 72 % (the average for adults from the survey in Northampton reported here) the saving would be 3.12 man-sieverts.

Table 3 extrapolates these results to Northamptonshire as a whole, both in terms of the potential reduction in radon dose and the number of lung cancers avoided annually from a countywide remediation programme in existing domestic properties. Marked differences in the potential benefits of the programme are seen, depending on the occupancy rate used.

	50 %Occupancy	**72 %Occupancy**	**80 %Occupancy**
Man-Sieverts per Year Avoided	12.8	18	20.5
Lung Cancers Averted Annually	0.4	0.6	0.7

Table 3 - Effect of Occupancy on the Benefits of the Existing Domestic Remediation Programme in Northamptonshire

These estimates nevertheless need to be treated with caution for a variety of reasons. Radon levels are known to vary markedly in different parts of the home (18), and at different times of the day (19). The proportion of time spent in the home may be only an approximation for exposure and health risk - much depends on where in the home people spend their time, and when they are in the home; However, the use of the NRPB protocol to assess domestic radon levels, which uses a weighted average of two rooms, may compensate for these variations. The patterns of behaviour – and indeed the amount of time spent in the home – also vary greatly within any population group, as the results presented here have shown. Exposures and health risks may thus be expected to show similar differences across the population. For some groups, the risks may thus be much less than these aggregate figures imply; for some groups much greater. In the case of lung cancers, it is also important to emphasise that the latency period may be long (typically 10-20 years or more). The health risks are thus affected by exposures some time in the past, and depend upon long-term exposures. The risk to health – and the associated benefits of remediation programmes – thus depend on how long people live at the same address (or in the same area), and upon their age. Lung cancers are, for example, unlikely to be induced in elderly people even though their home occupancy may be almost total. Equally, risks and benefits may be lower for young people, especially the more affluent or those in professional employment, who go out more often and tend to move house more frequently. The average time-span spent in one house in the UK before moving is 5.5 years (6), and such a move could be to outside the Affected Area, or to an unaffected house within the Affected Area.

Such patterns of behaviour need to be taken into account when planning an effective public health campaign to reduce risk from radon, which should target the specific groups within the population who are most at risk.

CONCLUSIONS

Current occupancy patterns for the general public in Northamptonshire, UK, have been assessed. The average for adults is found to be around 72 %, which is broadly similar to occupancy levels reported by other studies in the UK and USA, but somewhat lower than the NRPB assumption. Using this average occupancy level, it is possible to estimate the potential effectiveness of remediation programmes: for the current radon remediation programme in existing housing in Northamptonshire this suggests an annual dose reduction of around 18 man-sieverts, and the avoidance of around 0.6 lung cancers per year.

The results from this and other surveys nevertheless show marked variations in occupancy patterns across the population, both between different social groups and within any group. In general, therefore, groups who show higher occupancy levels - such as toddlers, young women with children and the elderly – are likely to receive significantly greater radon exposure than others. Whether this exposure is likely to translate into an increased health risk – and thus the actual benefits from remediation – will, however, depend on a number of factors, not considered in detail here, including the age of the individuals concerned, and the number of years they live in the affected home. Use of average data may thus lead to errors in the assessment both of health risks of radon exposures, and the potential benefits of radon remediation programmes. Greater attention to time activity patterns in assessing the risks of radon exposure and the effectiveness of remediation programmes is consequently required. These factors should be born in mind when planning targeted public health campaigns to reduce the risks of radon.

ACKNOWLEDGEMENTS

Part of the work reported here was carried out with the support of an EPSRC grant, which is gratefully acknowledged. The authors would also like to acknowledge the contribution of the other researchers who took part in the Northampton Air Pollution study, and the cooperation of the National Radiological Protection Board in the sampling of the Northamptonshire residential sample. However, the authors listed take full responsibility for the data presented in this paper and the conclusions drawn therefrom.

REFERENCES

1. International Commission of Radiological Protection. *The Health Effects of Inhaled Radon and its Progeny* In *Protection Against Radon-222 at Home and Work,* Annuls of the ICRP, 23, 7-13 (1994).

2. J.H.Lubin and J.D.Boice. *Lung Cancer Risk from Residential Radon : Meta-analysis of eight Epidemiological Studies.* Journal of the National Cancer Institute, 89(1), 49-57 (1997).

3. S.Darby, E.Whitley, P.Silcocks, B.Thakrar, M.Green,P.Lomas, J.C.H.Miles, G.Reeves, T.Fearn and R.Doll. *Risk of Lung Cancer associated with Residential Radon Exposure in South-West England : a case-control study.* British Journal of Cancer, 78(3), 394-408 (1998).

4. National Radiological Protection Board. *Human Exposure to Radon in Homes.* Documents of the NRPB, 1(1). Chilton, NRPB (1990).

5. National Radiological Protection Board. *Radon Affected Areas, Derbyshire, Northamptonshire and Somerset.* Documents of the NRPB, 3(4), Chilton, NRPB (1992).

6. A.R.Denman and P.S.Phillips. *A Review of the Cost Effectiveness of Radon Mitigation in Domestic Properties in Northamptonshire*. Journal of Radiological Protection. 18(2), 119-124 (1998).

7. C.A.Kennedy, A.M.Gray, A.R.Denman and P.S.Phillips. *A Cost-effectiveness Analysis of a Residential Radon Remediation Programme in the United Kingdom.* British Journal of Cancer 81(7) 1243-1247 (1999).

8. BEIR VI Report. *Health Effects of Exposure to Radon.* National Academic Press, ISBN 0-309-05645-4, Washington DC, USA, (1999).

9. G.M.Kendall, J.C.H.Miles, K.D.Cliff, B.M.R.Green, C.R.Muirhead, D.W.Dixon, P.R.Lomas and S.M.Goodridge. *Exposure to Radon in UK Dwellings.* NRPB Report R-272 (1994).

10. E.A.Francis. *Patterns of Building Occupancy for the General Public.* NRPB Memorandum M-129 (1986).

11. British Broadcasting Corporation. *The People's Activities and Use of Time.* BBC, Audience Research Department (1978).

12. A.R.Denman, S.P.Barker, S. Parkinson, F.Marley, and P.S.Phillips. *Do the UK workplace Radon Action Levels reflect the Radiation Dose received by the Occupants ?* Journal of Radiological Protection.19(1), 37-43 (1999).

13. R.W.Field, B.J.Smith, C.P.Brus, C.F.Lynch, J.S.Neuberger and D.J.Steck. *Retrospective Temporal and Spatial Mobility of Adult Iowa Women.* Risk Analysis. 19(5), 575-584(1998).

14. K.S.Liu, Y.L.Chang, S.B.Hayward, A.J. Gadgil, and A.V.Nero. *The Distribution of Lifetime Cumulative Exposures to Radon for California Residents.* Journal of Exposure Analysis and Environmental Epidemiology. 3(2), 165-179 (1993).

15. W.H. Dörre. *Time-activity-patterns of some selected small groups as a basis for Exposure Estimation : A Methodological Study.* Journal of Exposure Analysis and Environmental Epidemiology. 7(4), 471-491 (1997).

16. C.J.Tung, T.C.Chao, T.R.Chen, F.Y.Hsu, I.T.Lee, S.L.Chang, C.C.Liao, and W.L.Chen. *Dose Reconstruction for Residents living on Co-60 contaminated Rebar Buildings.* Health Physics, 74(6), 707-713 (1998).

17. M. Tufail, T.Rashid, A.B.Mahmood, and N.Ahmad. *Radiation Doses in Pakistani Homes.* The Science of the Total Environment, 142(3), 171-177 (1994).

18. P.S.Phillips and A.R.Denman. *Radon : a Human Carcinogen.* Science Progress, 80(4), 317-336 (1997).

19. J.C.H.Miles and R.A.Algar. *Variations in radon-222 concentrations.* Journal of Radiological Protection, 8(2), 103-105 (1988).