A Review of the Factors Affecting the Cost Effectiveness and Health Benefits of Domestic Radon Remediation Programmes

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Abstract. Radon levels in domestic properties can be sufficiently high to pose a health hazard, significantly increasing the risk of lung cancer. The distribution of high levels varies geographically. As a result, radon remediation programmes in the United Kingdom (UK) have been developed, firstly to find the houses with high levels, and then remediate these. Our group has extensively studied domestic remediation programmes in the U.K., principally in Northamptonshire, where 6.3% of existing houses exhibit radon levels greater than the UK Action Level of 200 Bq.m$^{-3}$, but also in other parts of the country. This analysis has addressed the influences of a number of different factors. Firstly, programmes in areas where more houses are over the Action level are necessarily more cost-effective. Secondly, cost-effectiveness is reduced if people do not take action to test, and then remediate, their houses, which is the case in practice. Therefore, radon awareness programmes in areas with a modest number of houses over the Action level can be more expensive, and therefore inappropriate, compared with other health interventions. Our studies have also demonstrated that the occupancy of the home, together with the ratio of radon levels upstairs and downstairs, has only a modest effect on the value of remediation. More significantly, remediation with an active pump eliminates diurnal variation, and night-time exposure is thus reduced while day-time exposure is not. The most significant impact on the value of remediation programmes, however, is whether the occupants smoke, as radon and smoking combine to produce a greater health risk. Unfortunately, surveys have shown that fewer smokers take action to test and remediate their homes, and many of those most at risk are consequently not reached by the current programmes. This paper presents a review of these issues, and considers the impact of the results on the design of future remediation programmes.

KEY WORDS: Radon Gas; Remediation; Action Level; Health Risk; Cost Effectiveness; Lung Cancer; smoking; occupancy

1. Introduction

Naturally occurring radon gas has a variable geographical distribution, and is concentrated in the built environment. Radon has been shown to cause increased numbers of lung cancers in miners when present at high levels in underground workings [1]. Reviews of the miners' studies suggest that levels found in some homes can give rise to increased lung cancer incidence, and this has been confirmed by recent case-control studies in South West England [2], and Germany [3]. The current scientific consensus, expressed in the BEIR VI report [4], is that the risk of lung cancer has a linear relation with increasing radon exposure, and that there is no threshold of risk. Recently, a collaborative analysis of 13 European studies has confirmed that there is an increased risk of lung cancer in the range 100 to 200 Bq m$^{-3}$, which is consistent with this linear interpolation [5].

In the United Kingdom (UK), the Radiation Protection Division of the Health Protection Agency (formerly National Radiological Protection Board (NRPB)) has designated a number of Affected Areas [6] where 1% or more of the homes have average seasonally-corrected radon levels above the UK domestic Action Level, currently 200 Bq m$^{-3}$. Northamptonshire is one such area, with 6.3% of houses above the Action Level [7]. Other countries have adopted different Action Levels, and varying strategies to encourage or coerce remediation. ICRP [8] have recommended an Action Level in the range 200 to 600 Bq.m$^{-3}$, while, for example, the Action Level in USA is 148 Bq.m$^{-3}$, and in Luxemburg is 150 Bq.m$^{-3}$. Ireland has adopted

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200 Bq.m\(^{-3}\) like the UK, while many other European countries use 400 Bq.m\(^{-3}\) for existing homes and 200 Bq.m\(^{-3}\) for new houses [9].

Our group has been studying domestic radon remediation programmes in Northamptonshire, and other areas in the UK which have been designated Radon Affected Areas (Figure 1). This analysis was first reported by Denman and Phillips [10], and since then our group has reviewed different aspects of such programmes. This paper reviews all these results, and the implications for public health policies to reduce the health risk from radon.

**Figure 1:** Radon map of UK, showing study areas

2. **Methodology**

The method for determining cost-effectiveness, which has been described in detail elsewhere, e.g. [11], involves measuring actual radon levels in a series of typical UK homes before and after remediation, and knowing the actual number of occupants, the costs of providing the remediation and any future running costs. Our early studies addressed existing properties, but more recent work has also looked at the potential effects of protecting new domestic properties. All homes were remediated by a single contractor abiding by the Radon Council guidelines. Originally, occupancy was estimated from previous work, but an average occupancy of 72% (17 hours 20 minutes per day) as calculated from a survey in Northamptonshire [12] has been adopted in later analyses. These factors were combined with radon level reduction to assess the dose saving achieved by the remediation.

The total costs of the programme were recorded. These included the costs of the initial measurements to find the affected houses, the charge made by the contractor for remediation work (which covers both wages and the equipment installed), the costs of retesting with etched-track detectors after remediation, and the costs of running and maintaining the remediation system installed. However, the costs of information campaigns, such as leaflet drops by NRPB, to warn the general public of the risks of radon, were not included. All costs were corrected for inflation using UK Retail Price Index published by the Office for National Statistics. The index for Repairs and Maintenance Charges was used to correct remediation costs. UK Value Added Tax (VAT) at 17.5%, which is payable by the householder on the remediation work, was applied. Finally, the total cost of each programme per annual dose saved was calculated. These values were
then used to determine the cost per life-year gained from the programmes brought about by the fall in the incidence of lung cancer.

More recent papers have extended the analysis to consider the Quality of Life of occupants with and without lung cancer, and then assessed the cost per quality-adjusted life-year (QALY) gained from remediation [13]. This use of a measure widely employed in the health economics literature and health policy debates has allowed for comparison of the cost effectiveness of remediation programmes with other interventions that can cut the incidence of various types of cancer. It has also meant that it has been possible to make a strong policy case for encouraging such programmes.

3. Results

The houses studied included 86 remediated domestic properties in Northamptonshire, with a total of 212 occupants, although some of these properties were remediated following the early papers. All houses were remediated using the sump and pump method, and final average radon levels were found to be well under 200 Bq.m\(^{-3}\). It was estimated that 1761 houses would have to have been tested in Northamptonshire, in order to yield 86 properties over the Action Level.

Kennedy et al. [14] reported that a domestic radon remediation programme in Northamptonshire has similar cost effectiveness as a number of other health interventions which have been adopted in the UK, including the UK breast cancer screening programme. The analysis included a single variant analysis, which studied the impact of a change in the value of a single variable used in the analysis. The results are shown in Figure 2.

\textbf{Figure 2:} \textit{Analysis of the sensitivity of remediation cost to study parameters}

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\includegraphics[width=\textwidth]{figure2.png}
\caption{Analysis of the sensitivity of remediation cost to study parameters}
\end{figure}

This suggests that the cost of treating lung cancer, the cost of remediating and the discount rates for maintenance have little effect on cost effectiveness. However, the percentage of houses over the Action Level, the percentage of householders remediating, the lifetime risk of lung cancer, the discount rate for life-years gained, and the life expectancy have a considerable effect.

4. Variation with Percentage of Housing with Radon Levels over the Action Level

The analysis was extended to houses in North Oxfordshire, where 15.83% of existing houses are over the action level, and part of Somerset (2.88%), where the single contractor had undertaken sufficient remediation works for statistical validity. This, combined with analysis of Northamptonshire data in smaller areas, permitted the comparison of the relative cost effectiveness of radon remediation programmes in areas with differing percentages of houses over the action level. As predicted by Kennedy et al. [14], and shown in Figure 3, remediation programmes in areas with more houses over the Action Level were shown to be more cost effective on the cost per life-year gained measure. More particularly, Coskeran et al. [15]
suggested that current radon remediation programmes in radon affected areas where less than 5% of houses are above the Action Level cannot be justified under the criteria used by the UK National Institute for Health and Clinical Excellence (NICE) guidance used to consider possible new health interventions.

**Figure 3** Comparison of cost per Life-Year gained and percentage of houses above the Action Level

5. **Participation by Householders**

In the period when the existing houses were remediated, householders were offered free testing. Those with results over the Action Level were advised, but not legally required, to remediate, and had to pay for any remediation themselves. When the series was first analysed, Bradley et al. [7] estimated that only 25.8% of houses in Northamptonshire have had radon measurements. This rose to 29.9% by 2002 [16]. Further, Bradley [17] found that only 10% of house-holders finding raised results have carried out remediation, although recently-implemented targeted local initiatives do appear to be having some impact on these figures [18]. This means that around 17,600 homes need to have been tested to yield the 86 remediated homes in Northamptonshire. The cost-effectiveness of a remediation programme is greatly reduced if householders do not remediate, as considerably more testing has to be carried out to achieve the same dose reduction, as shown by Coskeran et al. [15], and reproduced in Figure 4.

**Figure 4**: Cost per Life Year gained and the percentage of houses above the Action Level: effects of different remediation rates
6. Demographic Issues, Including Smoking Habits

The analysis reported above used the population average risk from radon to assess the health benefits of the remediation programme. However, the risk to an individual depends on their age, sex and smoking habits, as well as the radon exposure. The advent of the European Community Radon Software (ECRS) made it possible to extend the analysis by considering the risk to each individual. This required sending a questionnaire to each householder requesting details of the age, sex, and smoking habits of each occupant. Denman et al. [19] reported that those who remediate were older (Figure 5), had fewer children (a house occupancy of 2.20 compared to 2.47), and, most significantly, smoked less than the general population in Northamptonshire. Only 8.9% of those aged 18 to 64 in the group smoked, compared to an average of 28% in Northamptonshire.

Figure 5: Age of occupants of remediated houses compared to the population of Northamptonshire

As a consequence, Denman et al. [17] concluded that the radon remediation programme to date in Northamptonshire was around four times less cost cost-effective than the estimate made using collective risk factors. In addition to undermining the value of the programme when compared to other potential health interventions, this analysis showed that the programme was not reaching those most at risk – young families, and those who smoke.

Briggs et al. [12] considered the wide range of occupancy patterns, and its impact on the radon exposure received. Recently, Denman et al. [20] studied the hourly variation of radon levels before and after remediation with a sump and pump, and showed that the diurnal variation of radon levels was absent after remediation. Both of these findings will have modest effect on the cost-effectiveness.

7. Smoking Cessation Programmes in Radon Affected Areas

As noted by Denman et al. [17], smoking and radon are sub-multiplicative risk factors for lung cancer. Thus giving up smoking in a radon environment should reduce the risk of radon-induced lung cancers. The smoking cessation programme in Northamptonshire was studied by Denman et al. [21] who showed that the health benefit from smokers who live in a house with elevated radon levels giving up smoking is greater than reducing the radon levels, and continuing to smoke; although the greatest health benefit, of course, is
to do both. Thus smoking cessation programmes in radon Affected Areas have greater health benefits than elsewhere.

Those on the smoking cessation programme rated the radon health risk very low on their list of reasons for wanting to give up smoking, and research is ongoing to discover whether publicity about the combined effect of radon and smoking would increase the likelihood of giving up smoking.

8. Choice of Action Level

Denman et al [22] first reviewed the Northamptonshire series, and demonstrated that radon remediation programmes in areas with higher Action Levels cost less, but saved fewer lung cancers, and left residents in the houses with radon levels just below the Action Level with a significant dose. In this paper, and another [23] reviewing doses from radon in the workplace and the home, Denman et al. noted that the dose received by occupants of houses with radon levels close to 200 Bq.m$^{-3}$ received higher annual doses than workers in the workplace at 400 Bq.m$^{-3}$. The dose for this group was also higher than the limits in the Regulations for other radiation workers. Denman et al. extended this work to look at Action Levels below 200 Bq.m$^{-3}$ in Northamptonshire [24], and demonstrated that the curve of cost effectiveness against action level had a broad minimum around 250 to 300 Bq.m$^{-3}$. Denman et al [25] have extended this analysis to show that the minimum is similar for an area where a higher percentage of houses are over the Action Level, as shown in Figure 6.

**Figure 6:** Cost of Remediation per mSv averted for completed remediation programmes in NN6 area (14.65 % houses over Action Level), and Northamptonshire (6.3 %)

One feature of the series has been that there are fewer houses with initial radon levels in the range 200 to 300 Bq.m$^{-3}$ that have been remediated than would be predicted from a log-normal distribution. Denman et al. [21] interpreted this as indicating that householders decided that it was not worth remediating when there was only a moderately increased risk from radon.

Denman et al. [21] showed that a higher Action Level leaves a higher residual dose and risk to the remaining population. This dose is higher than and inconsistent with general annual radiation dose limits for the public. For example, at 400 Bq.m$^{-3}$ the maximum residual dose is higher than the 20 mSv limit for classified workers specified in the EU Basic Standards Directive. Therefore to reduce the dose from radon to match the 1 mSv limit for dose from general ionising radiation to the general public in the workplace, the Action Level would need to drop as low as 20 Bq.m$^{-3}$. However, recent work by Groves-Kirkby et al. [26]...
suggests that a component of the radon in UK homes comes from building materials and as a consequence radon levels cannot be reduced consistently much below 50 to 70 Bq.m^{-3} following remediation in the UK.

9. New Houses

In the UK, the Building Regulations require a radon-proof membrane to be fitted in new properties in radon Affected Areas. In addition, in Affected Areas with more than 10% of houses over the Action Level, a sump is fitted. Fitting a sump requires the householder to test the radon level after the building is occupied, and then fit a pump if radon levels are above the Action Level, at a much lower cost than fitting a complete system in an existing house. There is, however, no legal requirement in the UK for householders in new houses to carry out the testing, or to fit a pump.

Denman et al. [27] carried out a theoretical analysis and concluded that the current regulations were cost-effective in the high radon affected areas in Northamptonshire. However, Phillips et al. [28] noted that the UK system depended on the householder testing the radon level after occupation, and found that very few householders in a new housing estate knew about radon, let alone tested for it. In another estate in a high radon area, Denman et al. [29] found that some houses had radon levels over the Action Level, even with the building regulations precautions.

Coskeran et al. [30] studied the cost-effectiveness of a variety of options with new houses, and noted that the most cost-effective option was to build the houses without protection, measure for radon levels after occupation, and remediate any house with a raised level. However, this option requires householders or the house builder to test and then remediate the house. Such a test must be conducted after the house is occupied, with heating operating.

In the UK, the HPA have recently recommended that all new properties throughout the country should be provided with a radon-proof membrane [31]. Denman et al. [26], and Coskeran et al. [29] assumed that a radon-proof membrane would add £300 to the cost of the house. The requirement for such a membrane in all new homes should bring the price down – certainly, the HPA feel that their recommendations “could be undertaken without undue extra cost”. The work of our group, however, suggested that even in cases of areas with a relatively high proportion of properties above the Action Level, the use of such membranes is not the most cost effective method for protecting new properties. The extension of the use of radon-proof membranes to other parts of the UK would seem difficult to justify unless the cost of membranes has changed significantly.

10. Public Participation and Funding Issues

The costs involved in a remediation programme for existing properties can be shared between the individual householder and the local authority. In the UK, free testing was provided until around 2000 in Affected Areas, but householders, except in rare cases, had to find the cost of any necessary remediation. Several other policy options have been tried in other countries, such as making the measurement of radon levels and subsequent remediation a legal requirement, as in Sweden [32], or requiring action when houses are sold, as proposed in Canada [33]. Another alternative is to offer free remediation for homes with the highest radon levels, as has been adopted in Switzerland for levels over 1,000 Bq.m^{-3} [34]. Many countries have noted limited public response to the risks of radon. Ryan and Kelleher [35] interviewed 141 Irish householders who had discovered raised radon levels, and found that indecision and cost were the two major disincentives. Lee and MacDonald [36] have studied the public response to radon in the UK, and Suess [37] argues that public apathy is a major challenge.

In the UK there is now a requirement that property surveys include information about radon when houses are bought and sold in Affected Areas. This provides a form of market-solution to radon testing and remediation, as sellers need to consider radon when they put the house up for sale. However, this solution has a long time-scale, and would not result in testing and remediation of houses which were passed on to younger generations of the same family, or those where no property survey was undertaken at the time of purchase.
11. Conclusions

This review of the work published by our group studying the UK domestic radon remediation programmes in Northamptonshire and elsewhere has shown that a completed programme in radon Affected Areas can be cost-effective, and comparable to other health interventions which are considered justified and have been implemented. However, the research has also indicated the factors which reduce cost effectiveness, such as the take up of testing and remediating by the UK general public. This impacts on any aspiration to make radon remediation programmes more comprehensive by extending programmes into areas with fewer houses over the Action Level, or to respond to calls to lower the Action Level itself.

While it is attractive to formulate a public health programme to reduce all or most risk from radon in the home, the analysis presented here shows that adoption of a lower Action Level results in significantly increased expense and reduced cost effectiveness. This needs to be considered when planning public health strategies for a range of risks which are funded from finite resources.

The interaction of smoking and radon, and the fact that smokers are less likely to remediate, suggests that there is the possibility of reducing the risk from radon via smoking cessation campaigns and targeted publicity, which is being investigated further by our group. The lower uptake by young and larger families could be tackled by targeted funding, which has been adopted in some countries.

There is also the possibility that the current policy for targeting new homes may not be the most cost effective approach, and that new strategies need to be adopted, particularly in light of the HPA’s recent recommendation that the use of radon-proof membranes should be extended.

In short, national radon strategies must consider the need to locate those most at risk, and remediate such risks, bearing in mind the problem of overcoming public apathy on this issue.

REFERENCES


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