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Health effects of residential radon:

a European perspective at the end of 2002

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on behalf of the

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Abstract

Surveys of indoor radon concentrations, when taken together with estimates of the risk of lung cancer from studies in miners of uranium and other hard rocks suggest that residential radon is responsible for many thousands of deaths from lung cancer each year in Europe. The vast majority of these deaths are likely to occur in individuals who also smoke cigarettes. Because of the skewed nature of the distribution of the indoor radon concentrations in most populations, most of the deaths will occur in individuals who are exposed at moderate rather than at very high radon concentrations.

In order to enable appropriate policies to be developed for managing the consequences of exposure to radon, more reliable estimates of the risk of lung cancer resulting from it are needed. To achieve this, a European Collaborative Group on Residential Radon and Lung Cancer was initiated and its findings should be published in 2004.

Introduction

Surveys of the concentration of radon-222 gas in dwellings in various countries have been reviewed and summarized by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [(1)]. Data are available for over 20 European countries and these show that average radon concentrations vary widely, from <25 Bq m^{-3} in the Netherlands, the United Kingdom and Cyprus, to over 100 Bq m^{-3} in Estonia, Finland, Sweden, Luxembourg, the Czech Republic, Hungary and Albania (see Table 1). For many countries, the variation in indoor radon levels within the country is enormous, and individual dwellings with radon gas concentrations above 10,000 Bq m^{-3} have been found in Finland, Norway, Sweden, Belgium, Germany, Switzerland, the United Kingdom, the Czech Republic, and Spain.

Studies of radon-exposed miners

Underground mines of uranium and other igneous rocks tend to have high concentrations of radon gas and, up until now, studies of the mortality patterns of radon-exposed miners have formed the major body of evidence concerning the consequences of exposure to radon and its decay products. It is these studies, supported by studies on experimental animals and considerations of the distribution across the various organs of the body of the doses received after inhaling radon or its progeny, that have focussed attention on lung cancer rather than on other cancers[(2)] or on other diseases[(3)]. A recent worldwide review[(3)] has included over 60,000 miners from 11 studies (see Table 2). These miners were employed for an average of 5.7 years and their average cumulative exposure, measured in terms of Working Level Months (WLM) was 164.4 WLM. This is approximately equivalent to living in a house with a radon concentration of 2,000 Bq m^{-3}

for 20 years. By the end of the available period of follow-up, a total of 2,674 deaths from lung cancer had occurred and, in each of the 11 studies, there was an association between cumulative radon exposure, and risk of lung cancer that was unlikely to be due to chance (Table 2).

Although the size of the radon-related increase in lung cancer risk varied by more than an order of magnitude between the different studies (see Table 2), analysis of the information in the individual studies revealed some clear systematic trends in risk. The relative risk of lung cancer (i.e. the proportionate increase in the age-specific risk of lung cancer) increased linearly with increasing cumulative exposure, both overall and in the region <600 WLM[5], which is of greatest interest when considering the effects of residential exposures. After allowing for a minimum latent period of around five years between exposure and death, the percentage increase in risk was higher in the period around 10 years after exposure than at 20 or 30 years after exposure. Also, mines with low radon concentrations had a higher percentage increase in risk per unit exposure than mines with high radon concentrations or, equivalently, a given total exposure was associated with a greater increase in risk if it was received over a longer rather than a shorter time period. These systematic trends have enabled the US National Research Council's BEIR VI Committee to summarize the effects of radon exposure in the miners' studies in a statistical model which can be used for predicting the effects of radon exposure in other populations[3].

In most of the studies of miners, the majority of the men would have been cigarette smokers and this will have had an effect on their lung cancer risk that is likely to have been at least as big, or even bigger than, their radon exposure. Detailed smoking histories were not available in the miners studies, but for six of the studies there was some information on smoking habits and this has enabled separate dose-response relationships to be derived for lifelong non-smokers and for others. In both groups lung cancer risk increased with cumulative exposure and the increase in *relative risk* per unit exposure was about three times greater for never-smokers than others[3]. Therefore, as the *absolute risks* of lung cancer are at least 10 times higher in cigarette smokers than in lifelong non-smokers, these data suggest that the increase in *absolute risk* per unit radon exposure will be greater in cigarette smokers than in lifelong non-smokers by at least a factor of three.

Prediction of lung cancer risks from the miners' studies to the population of the United Kingdom

Recent estimates suggest that the average annual dose of ionizing radiation received by population of the UK is 2,600 µSv (see Table 3). Although the UK has one of the lowest average indoor radon concentrations in Europe, radon accounts for half the total dose, and its contribution is more than three times that attributable to medical radiation, the next most important source.

Lung cancer is the commonest fatal cancer in the UK and is currently responsible for nearly 35,000 deaths per year in a population of 59 million people. Combination of the BEIR VI summary risk model for the risk of lung cancer with the average residential radon concentration in the UK, data on UK smoking habits, and data on lung cancer risks in lifelong non-smokers, suggests that active smoking is responsible for 89.4% of UK lung cancer deaths, and that residential radon is responsible for 6.5% or around 2275 deaths per year (see Table 4), making radon the second most important cause of lung cancer after cigarette smoking. Of the 6.5% of lung cancer deaths that are attributable to radon, 5.5% are caused by radon and smoking acting jointly, in the sense that the lung cancer could have been avoided either by avoiding smoking or by avoiding exposure to radon, and this suggests that a reduction in the number of people in the population who smoke would have a substantial impact on the number of deaths attributable to radon. There remains only 1% of lung cancer deaths in the UK attributable to radon acting alone.

Calculations such as those shown in Table 4 can be repeated for age- and sex-specific subgroups of the population and these suggest that 62% of the deaths attributable to radon occur in males (see Table 5), reflecting the fact that in the past males have, on average, smoked more than females. Also, it seems likely that two-thirds of radon-attributable deaths occur in individuals aged between 55-74 years, with the remainder approximately equally divided between individuals aged 35-54 and 75+ years, and very few occurring in individuals under the age of 35 years.

The risk of lung cancer experienced by an individual will be determined both by smoking status and by residential radon concentration. At the UK average concentration of 20 Bq m-3, the cumulative risk of death from lung cancer by age 85 years in lifelong non-smokers is estimated to be around 0.8% (see Table 6). This would be reduced very slightly, to 0.7%, if residential radon concentrations were, hypothetically, brought down to zero while it would rise to 1.4% at 200 Bq m^{-3}, the level at which it is recommended in the UK that action be taken to reduce radon levels, and further to 2.2% at 400 Bq m^{-3}. For cigarette smokers the cumulative risk of lung cancer by age 85 at zero radon exposure is much higher, at 29.1%. The predicted absolute increases in risk attributable to radon exposure are also much higher in smokers than in non-smokers, and the cumulative risk of lung cancer by age 85 are predicted to be 30.4%, 40.0%, and 49.3% at radon concentrations of 20, 200 and 400 Bq m^{-3} respectively.

For a population of individuals the number of radon-induced deaths attributable to any given range of radon concentrations is determined not only by the individual risks but also by the distribution of residential radon concentrations. In the UK, as in most other countries, this distribution has been shown to be highly skewed with a long upper tail[(4)]. When the distribution of radon concentrations across dwellings is combined with the individual risks implied by the BEIR VI model, it can be seen that the proportion of lung cancer deaths attributable to residential radon that occur as a result of exposures at concentrations above the currently recommended action level of 200 Bq m^{-3} is only around 10%, with another 13% attributable to concentrations in the range 100-199 Bq m^{-3} (Table 7). Over one third of radon-attributable deaths in the UK are estimated to occur with radon concentrations of less than 25 Bq m^{-3} and around 20% each at levels in the ranges of 25-49 Bq m^{-3} and 50-99 Bq m^{-3}.

European studies of residential radon and lung cancer

In the studies of radon-exposed miners the average exposure rate is more than an order of magnitude greater than average indoor exposures, while the average duration of exposure is short, at less than six years. The miners are almost all adult males, and the available information about both their radon exposure and their smoking habits is crude and subject to sizeable errors. Furthermore, the conditions of exposure in the mines differ substantially from those in homes, with the miners carrying out substantial amounts of heavy work in an atmosphere polluted by dust and fumes. There is, therefore, great uncertainty in assuming that the effects of residential radon can be accurately predicted from models derived using data on the effects of radon in miners, and direct estimates of the risks of residential radon are needed.

The first direct studies of residential radon were carried out in Sweden and used building characteristics and ground conditions as indicators of the likely level of indoor radon concentration[7-9]. It was soon appreciated, however, that such surrogate measures were not sufficiently accurate, and more recent studies have measured indoor radon concentrations directly, usually by means of alpha-track detectors left in place for a substantial period of time in order to reduce the effects of diurnal and seasonal variation in radon concentrations. The studies either focussed on individuals who had been living in their present home for a substantial period of time or measured radon concentrations in past as well as present homes. To date, information on 14 such studies in Europe is available. These have been carried out in Sweden, Finland, the United Kingdom, Germany, the Czech Republic, Italy, Spain, Austria and France, and they include a total of over seven thousand individuals with lung cancer (see Table 8). All but one have taken the form of a case-control study, in which detailed residential and smoking histories have been gathered for a series of individuals with lung cancer and a comparable series of control subjects who had not developed the disease. The remaining study was cohort in design and included all people who had lived in the Middle Bohemian Pluton for a period of 3 years since 1960[17]. In most of the studies the average measured radon concentration was above 100 Bq m^{-3}, and within all the studies there was a wide range of radon concentrations.

After adjusting for smoking, all but one of the studies estimated that the risk of lung cancer tended to increase with increasing residential radon concentration and the estimates of relative risk at 100 Bq m^{-3} compared with 0 Bq m^{-3} ranged from 0.98 to 2.48 in the 14 studies. However, despite the large size of most of the studies and also the wide range of radon concentrations experienced by the subjects, the estimated effect of the radon was significantly different from no effect in only five of the studies.

Rather than measuring the current concentration of radon in the air of all the homes of interest, an alternative method of assessing residential radon histories is to estimate an individual's cumulative radon exposure. This can be done by considering the accumulation of the long-lived radon decay product Pb-210 implanted in the glass surface of an object, such as a picture frame, that has been on display in all the subject's homes over a substantial period of time. The long-lived Pb-210 gives rise to a shorter lived product, Po-210, which can be measured using passive alpha track detectors. From this measurement an estimate can be made of the cumulative radon exposure in the rooms where the glass object has been kept. The uncertainties associated with this method of estimating radon histories have not yet been fully documented, but it should largely address the difficulties caused by missing measurements in subjects' previous home, by random year-to-year variations in radon concentrations due to fluctuations in the weather, and by the fact that in some countries residential radon concentrations may have changed systematically over time, for example because of a tendency to reduce indoor ventilation rates(24), which would mean that air concentrations measured at the present time would be systematically biased compared with previous values. At the present time only one European study has published a risk estimate based on cumulative exposure histories from surface monitors(25). This included 110 subjects with lung cancer and 231 control subjects, all of whom were never smokers. The risk estimate obtained from the surface monitors was about twice that obtained for the same subjects from alpha-track measurements of radon gas.

European Collaborative Group on Residential Radon and Lung Cancer

It is impossible to obtain a satisfactory overview of the various studies of the effects of residential radon either from summaries such as those given in Table 8, or from reading the original publications. More formal attempts to combine the published data into a single summary risk estimate[23,4] have suggested a significant association, with the risk of lung cancer for homes with measured radon concentrations of 100 Bq m^{-3} about 6 to10 per cent higher than at 0 Bq m^{-3}. Estimates such as these are, however, limited by the fact that in the original study publications the information presented inevitably varies considerably from study to study, as do the inclusion criteria and method of analysis. In addition it is impossible, based only on the published data, to carry out a satisfactory investigation of the consistency of the different studies, or to explore the effect of possible modifying factors, such as smoking. To overcome these issues a European Collaborative Group on Residential Radon and Lung Cancer has been initiated and a similar project is underway in North America[26]. The European group has the objective of bringing together the original individual data from the European studies in such a way that, as far as possible, takes into account differences which may exist in the design of the studies, the smoking histories of individuals, or the radon dosimetry techniques employed in each study. Where it is appropriate, the data from the participating studies are being pooled to obtain more precise estimates of the risk of lung cancer from residential radon exposure, and the extent to which its effect is modified by smoking habits. It is possible that some of the existing studies of residential radon may suffer from design limitations that render them unsuitable for consideration in the Collaborative Analysis, and therefore the following criteria have been set up for participation in the group:

1. Subjects with lung cancer selected according to clearly defined criteria.

2. Control subjects selected according to explicit criteria and in such a way that they are representative of the underlying population from which the cases were drawn.

3. Detailed residential histories going back at least 15 years available both for subjects with lung cancer and for controls.

4. Long term measurements of radon gas obtained for the majority of residences occupied by subjects going back at least the previous 15 years.

5. Data on individual smoking habits available for all participants gathered by interview or postal questionnaire from the subject in person or from his or her next of kin.

6. Information available on the completeness of the study, ie the proportion of the target groups of cases and controls that were included in the study.

All the studies listed in Table 8 with 200 or more lung cancers satisfied the above criteria and the investigators have joined the Collaborative Group. Many of the smaller studies also satisfied the criteria and some of the study investigators have also joined the Group.

In order to enable comparable data from all the participating studies to be prepared, a Common Data Format and uniform inclusion criteria have been agreed by the Collaborative Group. The principles of the analysis were also agreed in advance by the group and included a decision to focus primarily on the residential radon concentration in the 30-year period ending 5 years prior to the date of diagnosis of lung cancer (or comparable index date for controls). Many subjects had lived at more than one address during this 30-year period and, in deriving summary measures of the residential radon exposure for each study subject, account needs to be taken of this by weighting the measurements for the different addresses according to the length of time that each individual spent there. In addition, estimates need to be constructed for past residences in the 30-year period where no measurement could be obtained, to obtain summary measures reflecting the exposure history during the entire 30-year period.

It has been agreed by the Collaborative Group to base analyses of the association between residential radon and lung cancer on the method of maximum likelihood, and to carry out analyses that consider radon as a continuous variable as well as analyses that consider radon as a categorical variable and, for the analyses that consider radon as a categorical variable, the cut-points have been specified *a priori*.

Issues in the analysis of studies of residential radon

As mentioned above, the smoking of manufactured cigarettes is the major cause of lung cancer in most Western populations. None of the studies of residential radon and lung cancer have found a strong correlation between smoking habits and residential radon concentrations, but the risk of lung cancer resulting from cigarette smoke is so great (see Table 6) that even a weak correlation could have an important effect on the estimated radon risk unless its confounding effect is fully removed. Furthermore, it is essential to remove the possible confounding effect of smoking in a way that takes account of the fact that the risks of smoking will differ from country to country and may also differ between men and women within the same country. The reasons for this are that within the various different European countries, cigarette smoking became popular at different times, different products are smoked in different amounts, and within a country the smoking habits of men and women at any given time often differ substantially. For example, cigarette smoking became popular among men in the UK well before World War II, but among Italian females the habit did not become prevalent until well after it. The result of these differing trends in smoking habits is that in the studies of residential radon the apparent effect of smoking may well differ substantially from country to country and also between men in women in the same country. An example of the possible magnitude of such differences is shown in Table 9 in which the cumulative risks of death from lung cancer by age 75 are compared for two UK studies, one carried out in 1950 and one carried out 40 years later in 1990. Among lifelong non-smokers, the risk was thought to be similar in men and women, and not to have changed with time. However, for current cigarette smokers the risk among men more than doubled between the two studies, while the risk among women increased by a factor of nearly 10. Table 9 also shows that the risks of lung cancer among former smokers, who now account for a substantial proportion of European populations, are substantially different both from the risks among lifelong smokers and from the risks among current cigarette smokers, and also that they differ between men and women.

Another issue that affects the assessment of the risks associated with residential radon is uncertainty in the assessment of radon concentrations. All the estimates shown in Table 8 have been obtained using standard statistical methodology in which it is assumed that the average radon concentration to which an individual has been exposed can be assessed without uncertainty. However, this assumption is usually violated in two different ways. Firstly, as already mentioned, in most of the studies there are some time-periods for which it is not possible to obtain a radon measurement for some individuals, for example, because the home previously occupied by the subject had been demolished and the best that can be done for such missing periods is to estimate the likely radon concentration based on measurements taken in other comparable homes in the same area. Secondly, even where it has been possible to obtain a measurement, the measured value will be subject to uncertainty in the sense that repeated measurements in the same home vary with a coefficient of variation of around 50%[27,14]. These two different sources of uncertainty will have different effects on the results of an analysis that has been carried out using standard techniques[28]. Missing values that have been replaced by estimates will cause confidence intervals to be wider than they would otherwise have been, and are undoubtedly a contributing factor in the low power of the case-control studies in shown in Table 8. In contrast, the presence of uncertainty in measured residential radon concentrations will cause the estimated effect of the radon using standard techniques of analysis to be biased towards zero compared with its true value. For two of the case-control studies shown in the Table 8, analyses have been carried out that take this bias into account[27,14]. For these studies, the estimated relative risks of lung cancer at 100 Bq m^{-3} compared with 0 Bq m^{-3} using the standard methods were 1.10 (95% confidence interval 1.01, 1.22) and 1.08 (0.97, 1.20), while the estimates taking account of measurement uncertainty were somewhat higher, at 1.17 (1.03, 1.37) and 1.12 (0.95, 1.33). Thus, in both studies the effect of adjusting for measurement error has had a substantial effect on the estimated risks associated with residential radon.

Both the issue of careful adjustment for smoking and the issue of bias caused by uncertainties in the assessment of residential radon concentrations are being considered in detail by the European Collaborative Group in their analyses.

Conclusions

The indoor radon concentrations that have been observed in various European countries, when taken together with estimates of the risk of lung cancer based on studies of underground miners, suggest that radon is the second most important cause of lung cancer after smoking in most, if not all, European countries and that it is likely to be responsible for many thousands of deaths each year in Europe. The distribution of radon concentrations is highly skewed in most countries and therefore only a very small proportion of the deaths attributable to radon are likely to occur at the very highest radon concentrations, with a much larger proportion occurring as a result of lower radon concentrations, because of the much larger number of people exposed at these levels. The vast majority of radon attributable deaths are likely to be caused in conjunction with cigarette smoke in the sense that the cancer could have been avoided by avoiding either the smoking or the radon exposure.

There is great uncertainty in predicting the effects of exposure to residential radon from the experience of occupationally exposed underground miners. To reduce this uncertainty more than a dozen detailed studies designed to estimate directly the risks associated with residential exposures have been carried out in Europe. A European Collaborative Group on Residential Radon and Lung Cancer has been formed with the objective of bringing together the original data from the major studies in order to provide more reliable estimates of the risk of lung cancer resulting from residential radon and lung cancer than are provided by the individual studies. At the time of writing, its analyses are underway and the findings should be published in 2004.

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Table 1. Radon gas concentrations in dwellings in various European countries. Based on UNSCEAR.[1]

Region	Country	Population in 1996 (10^6)	Radon concentration ($Bq\ m^{-3}$)	
			Arithmetic mean	Maximum value
Northern Europe	Denmark	5.24	53	600
	Estonia	1.47	120	1,390
	Finland	5.13	120	20,000
	Lithuania	3.73	55	1,860
	Norway	4.35	73	50,000
	Sweden	8.82	108	85,000
Western Europe	Belgium	10.16	48	12,000
	France	58.33	62	4,690
	Germany	81.92	50	>10,000
	Luxembourg	0.41	110	2,500
	Netherlands	15.58	23	380
	Switzerland	7.22	70	10,000
	United Kingdom	58.14	20	10,000
Eastern Europe	Czech Republic	10.25	140	20,000
	Hungary	10.05	107	1,990
	Poland	38.60	41	432
	Romania	22.66	45	1,025
	Slovakia	5.35	87	3,750
Southern Europe	Albania	3.40	120	270
	Croatia	4.50	35	92
	Cyprus	0.76	7	78
	Greece	10.49	73	490
	Italy	57.23	75	1,040
	Portugal	9.81	62	2,700
	Slovenia	1.92	87	1,330
	Spain	39.67	86	15,400

Table 2: Lung cancer mortality in cohort studies of underground miners occupationally exposed to radon. Based on BEIR VI Committee.[(3)]

Study	Type of mine	Number of exposed miners	Mean total WLM	Mean duration of exposure (years)	Number of lung cancer deaths	Percentage increase in age-specific risk of lung cancer per WLM[a]	95% confidence interval
Yunnan, China	Tin	13,649	286.0	12.9	936	0.16	0.1-0.2
W. Bohemia, Czech Republic	Uranium	4,320	196.8	6.7	701	0.34	0.2-0.6
Colorado, USA[b]	Uranium	3,347	578.6	3.9	334	0.42	0.3-0.7
Ontario, Canada[c]	Uranium	21,346	31.0	3.0	285	0.89	0.5-1.5
Newfoundland, Canada	Fluorspar	1,751	388.4	4.8	112	0.76	0.4-1.3
Malmberget, Sweden	Iron	1,294	80.6	18.2	79	0.95	0.1-4.1
New Mexico, USA	Uranium	3,457	110.9	5.6	68	1.72	0.6-6.7
Beaverlodge, Canada	Uranium	6,895	21.2	1.7	56	2.21	0.9-5.6
France	Uranium	1,769	59.4	7.2	45	0.36	0.0-1.2
Port Radium, Canada	Uranium	1,420	243.0	1.2	39	0.19	0.1-0.6
Radium Hill, Australia	Uranium	1,457	7.6	1.1	31	5.06	1.0-12.2
Total[d]		60,606	164.4	5.7	2,674		

a The working level (WL) is defined as any combination of the short-lived radon progeny in one litre of air that results in the ultimate release of 1.3×10^5 MeV of potential α-particle energy. Exposure to this concentration for 170 h (or twice this concentration for half as long, etc.) is defined as a working level month (WLM). An individual living in a house with a radon concentration of 20 Bq m^{-3} will be exposed to 0.08 WLM per year.

b Totals given exclude data above 3200 WLM.

c Values given include all uranium miners, including those with previous gold mining experience.

d Totals adjusted for miners and lung cancers included in both Colorado and New Mexico studies.

Table 3. Annual exposure of the UK population from all sources of radiation. Based on Hughes.[6]

Source	Annual collective dose (man Sv)	Average annual dose (μSv)
Natural		
Cosmic	15,000	260
Gamma	20,200	350
Internal	17,300	300
Radon	74,900	1,300
Artificial		
Medical	21,400	370
Occupational[a]	430	7
Fallout	290	5
Discharges[b]	20	0.4
Products	20	0.4
Total (rounded)	**150,000**	**2,600**

[a]Some 80% from natural sources
[b]Some 20% from natural activity

Table 4: Causes attributed to the lung cancer deaths occurring each year in the United Kingdom. Based on Darby *et al.* [4]

Cause	Number of lung cancer deaths	Percentage attributed	
Not caused by active smoking or by residential radon	3,351	9.6	
Caused by radon but not by smoking	349	1.0	6.5 due to residential radon (1.0 + 5.5)
Caused by smoking and radon (avoidance of either of which would have avoided that particular lung cancer)	1,926	5.5	89.4 due to active smoking (5.5 + 83.9)
Caused by smoking and not by radon	29,332	83.9	
Total no. of lung cancer deaths	34,958	100.0	

Calculation used 1998 UK national data for numbers of lung cancer deaths, population size and smoking habits. Lung cancer death rate in lifelong non-smokers taken from a US prospective study of mortality, adjusted for the lower average radon level in the UK. Average radon exposure assumed to be 20 Bq m^{-3}. Radon risks taken from studies of underground miners using the BEIR VI exposure/age/concentration model with submultiplicative joint effect of smoking and radon.[3]

Table 5: Distribution of lung cancer deaths attributable to residential radon in the United Kingdom each year by age and sex. Based on Darby *et al.*[4]

Age	Males	Females	Total
<35	1.5	1.5	3 (<1%)
35-54	224	161	385 (17%)
55-74	962	554	1,516 (67%)
75+	218	153	371 (16%)
All ages	1,405 (62%)	869 (38%)	2,275 (100%)

Table 6: Effect of various residential radon concentrations on the cumulative risk (%) of death from lung cancer to age 85. Based on Darby *et al.*[4]

	Residential radon concentration (Bq m^{-3})				
	0	**20[a]**	**100**	**200**	**400**
Lifelong non-smoker	0.7	0.8	1.0	1.4	2.2
Cigarette smoker	29.1	30.4	34.8	40.0	49.3

Radon risks taken from studies of underground miners using the BEIR VI exposure/age/concentration model for radon risks with submultiplicative joint effect of smoking and radon.[3] Lung cancer death rates taken from 1988 UK national data, a US prospective study for lifelong non-smokers (with adjustment for the lower average radon concentration in the UK compared with the US), and a recent study of UK lung cancers for cigarette smokers. If, for one particular category, the lung cancer rates per 10^5 in all the five year age groups before age 85 add up to c, then the cumulative risk by age 85 is $1-\exp(-5c/10^5)$. Thus, cumulative risks depend only on age-specific lung cancer rates and not on competing causes of death.

[a]UK average residential radon concentration.

Table 7: Lung cancer deaths attributable to residential radon in the United Kingdom each year by residential radon concentration. Based on Darby *et al.*[4]

Range of residential radon concentrations (Bq m^{-3})	Percentage of homes in range	Deaths attributable to residential radon	
		Number	Percent
0-24	75.3	812	35.7
25-49	14.9	492	21.6
50-99	6.8	445	19.6
100-199	2.3	296	13.0
200+	0.7	230	10.1
Total	100.0	2,275	100.0

Table 8. The major European studies of residential radon and lung cancer

Study and reference	Date of publication	No. of lung cancers	No. of controls	Ave. radon (Bq m^{-3})	Relative risk 100 Bq m^{-3} vs 0 Bq m^{-3}	95% CI
Stockholm[10]	1992	201	378	130	1.55[a]	(1.23-2.00)[a]
Swedish nationwide[11]	1994	1,281	2,576	110	1.10	(1.01-1.22)
S. Finland[12]	1996	164	331	220	1.80	(0.90-3.50)
Finnish nationwide[13]	1996	517	517	100	1.11	(0.94-1.31)
SW England[14]	1998	982	3,185	60	1.08	(0.97-1.20)
W. Germany[15]	1998	1,449	2,297	50	0.98[b]	(0.82-1.17)[b]
Swedish never-smokers[16]	2001	258	487	80	1.28	(0.95-2.05)
Czech Republic[17]	2001	210	11,794	500	1.09	(1.02-1.21)
Italy-Trento[18]	2001	138	210	130	1.40	(0.30-6.60)
Spain[19]	2002	163	241	130	2.48	(1.12-5.48)
Austria[20]	2002	194	198	200	1.25	(1.08-1.43)
France[21]	2002	486	984	141	1.04	(0.99-1.11)
E. Germany[22]	In press	1,053	1,667	80	1.08	(0.97-1.20)
Italy-Rome	-[c]	384	405	110	1.10	-

[a]Estimate derived from Lubin and Boice[23]
[b]Estimate for radon-prone area only: 1.13 (0.88-1.46)
[c]Not yet published. Information supplied by F. Bocchicchio and F. Forastiere.

Table 9. Cumulative risks (%) of death from lung cancer by age 75 in 2 UK studies. Based on Peto *et al.*[29]

Smoking status	Men		Women	
	1950	1990	1950	1990
Lifelong non-smokers	~0.4	~0.4	~0.4	~0.4
Former smokers	2.9	5.5	0.9	2.6
Current cigarette smokers	5.9	15.9	1.0	9.5