Cite this article as: BMJ, doi:10.1136/bmj.38308.477650.63 (published 21 December 2004)

Papers

BMJ: first published as 10.1136/bmj.38308.477650.63 on 21 December 2004. Downloaded from http://www.bmj.com/ on 29 March 2024 by guest. Protected by copyright.

Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies

S Darby, D Hill, A Auvinen, J M Barros-Dios, H Baysson, F Bochicchio, H Deo, R Falk, F Forastiere, M Hakama, I Heid, L Kreienbrock, M Kreuzer, F Lagarde, I Mäkeläinen, C Muirhead, W Oberaigner, G Pershagen, A Ruano-Ravina, E Ruosteenoja, A Schaffrath Rosario, M Tirmarche, L Tomášek, E Whitley, H E Wichmann, R Doll

Abstract

Objective To determine the risk of lung cancer associated with exposure at home to the radioactive disintegration products of naturally occurring radon gas

Design Collaborative analysis of individual data from 13 case-control studies of residential radon and lung cancer.

Setting Nine European countries.

Subjects 7148 cases of lung cancer and 14 208 controls.

Main outcome measures Relative risks of lung cancer and radon gas concentrations in homes inhabited during the previous 5-34 years measured in becquerels (radon disintegrations per second) per cubic metre (Bq/m^3) of household air.

Results The mean measured radon concentration in homes of people in the control group was 97 Bq/m^3, with 11% measuring >200 and 4% measuring >400 Bq/m^3. For cases of lung cancer the mean concentration was 104 Bq/m^3. The risk of lung cancer increased by 8.4% (95% confidence interval 3.0% to 15.8%) per 100 Bq/m^3 increase in measured radon ($P=0.0007$). This corresponds to an increase of 16% (5% to 31%) per 100 Bq/m^3 increase in usual radon—that is, after correction for the dilution caused by random uncertainties in measuring radon concentrations. The dose-response relation seemed to be linear with no threshold and remained significant ($P=0.04$) in analyses limited to individuals from homes with measured radon <200 Bq/m^3. The proportionate excess risk did not differ significantly with study, age, sex, or smoking. In the absence of other causes of death, the absolute risks of lung cancer by age 75 years at usual radon concentrations of 0, 100, and 400 Bq/m^3 would be about 0.4%, 0.5%, and 0.7%, respectively, for lifelong non-smokers, and about 25 times greater (10%, 12%, and 16%) for cigarette smokers.

Conclusions Collectively, though not separately, these studies show appreciable hazards from residential radon, particularly for smokers and recent ex-smokers, and indicate that it is responsible for about 2% of all deaths from cancer in Europe.

Introduction

In many countries exposure in the home to short lived radioactive disintegration products of the chemically inert gas radon-222 is responsible for about half of all non-medical exposure to ionising radiation.[1] Radon-222 arises naturally from the decay of uranium-238, which is present throughout the earth's crust. It has a half life of four days, allowing it to diffuse through soil and into the air before decaying by emission of an α particle into a series of short lived radioactive progeny. Two of these, polonium-218 and polonium-214, also decay by emitting α particles. If inhaled, radon itself is mostly exhaled immediately. Its short lived progeny, however, which are solid, tend to be deposited on the bronchial epithelium, thus exposing cells to α irradiation.

Air pollution by radon is ubiquitous. Concentrations are low outdoors but can build up indoors, especially in homes, where most exposure of the general population occurs. The highest concentrations to which workers have been routinely exposed occur underground, particularly in uranium mines. Studies of exposed miners have consistently found associations between radon and lung cancer.[2,3] Extrapolation from these studies suggests that in many countries residential radon, which involves lower exposure in much larger numbers of people, could cause a substantial minority of all lung cancers. This is of practical relevance because radon concentrations in existing buildings can usually be reduced at moderate cost—for example, by increasing underfloor ventilation—while low concentrations can usually be ensured at reasonable or low cost in new buildings—for example, by installing a radon proof barrier at ground level. These extrapolations, however, depend on uncertain assumptions because the levels of exposure in miners that produced evident risk were usually much higher, lasted only a few years, and took place under different particulate air and other conditions.[1–3] Moreover, history on smoking is often lacking, or limited, in the studies of miners and some miners were also exposed to other lung carcinogens such as arsenic.

Studies to estimate directly the risk of lung cancer associated with residential radon exposure over several decades have been conducted in many European countries. Individually these studies have not been large enough to assess moderate risks reliably. Greater statistical power can be achieved by combining information from several studies, but this cannot be done satisfactorily from published information. Urban areas tend to have lower radon concentrations than rural ones as the underlying rock is usually sedimentary and more people live upstairs in apartments. Urban areas also usually have a higher prevalence of smoking. Hence, radon concentrations in homes tend to be negatively correlated with smoking,[4–6] and a large dataset is needed to correct for this reliably. We therefore brought together and reanalysed individual data from all European studies of residential radon and lung cancer that satisfied certain criteria.

Methods

Included studies

This collaboration included all 13 European studies that registered over 150 people with lung cancer and 150 controls, incorporated detailed smoking histories, and sought radon measurements[7] in homes that these individuals had lived in during the past 15 years or more. Information on demographic and lifestyle variables was compiled for each person by using a common format, and radon measurements were expressed in becquerels (Bq) (radon disintegrations per second) per cubic metre of household air.

On the basis of information from the studies on miners,[2 3] we assumed that the period of radon exposure most relevant to the risk of lung cancer was the 30 years ending five years before the diagnosis of (or death from) lung cancer or, for those in the control group, before a corresponding index date. We excluded individuals for whom no radon measurements for this 30 year period were available or with unknown smoking status. The available radon measurements covered a mean of 23 years. For relevant homes where radon measurements could not be obtained (for example, because the house had been demolished), we estimated the concentration indirectly as the mean of all the radon measurements in the residences of control group members in the relevant study area. Finally, to obtain the "measured radon concentration" for each individual, we calculated a time weighted average of the radon concentrations in all the homes occupied over the past 5-34 years with weights proportional to the length of time the individual had lived in each.

Statistical methods

We assessed the association between radon and lung cancer in two ways. Firstly, a model was fitted in which the risk of lung cancer was proportional to $(1+\beta x)$ where x is measured radon concentration and β the proportionate increase in risk per unit increase in measured radon. Secondly, we subdivided cases and controls by categories of measured radon concentration and plotted relative risks across different categories against estimated mean exposure levels in those categories. In both types of analysis, confounding was controlled through stratification.

Radon measurements made in the same home but in different years show considerable random variability, indicating some uncertainty in the measured radon concentration for each individual. Further random uncertainty arises as radon concentrations in some homes could not be measured and were estimated indirectly. Both types of uncertainty lead to "regression dilution," whereby the relation of risk to measured radon concentration is substantially weaker than the relation of risk to "usual" (that is, true long term average) concentration.[5 6 8] We calculated dose-response relations both with and without correction for this and estimated a time weighted average usual radon concentration for each individual (see www.ctsu.ox.ac.uk/radonmethods for further details).

Results

Our analysis included 7148 people with lung cancer and 14 208 controls. For cases of lung cancer the mean measured radon concentration was 104 Bq/m^3 while for controls the weighted average of the study specific means, with weights proportional to numbers of cases of lung cancer, was 97 Bq/m^3 (table 1). Among controls, the percentage who were lifelong non-smokers increased as radon concentration increased (percentages were 39%, 40%, 41%, 46%, and 48% for measured radon <100, 100-199, 200-399, 400-799, and ≥ 800 Bq/m^3 after stratification for study, age, sex, and region of residence; $P=0.001$ for trend).

Table 1 European case-control studies of residential radon and lung cancer

Study	Mean year of diagnosis	Mean measured radon concentration (Bq/m^3)*	
		Lung cancers	Controls
Austria[9]	1983	267	130
Czech Republic[10]	1981	528	493
Finland (nationwide)[11]	1989	104	103
Finland (south)[12]	1982	221	212
France[13]	1995	138	131
Germany (eastern)[14]	1994	78	74
Germany (western)[14]	1993	49	51
Italy[15]	1995	113	102
Spain[16]	1993	123	137
Sweden (nationwide)[17]	1982	99	94
Sweden (never smokers)[18]	1990	79	72
Sweden (Stockholm)[19]	1985	131	136
United Kingdom[6]	1991	57	54
All studies	1990	104	97†

*Estimate for each individual is time weighted average of measurements in different residences 5-34 years earlier.
†Weighted average, with weights proportional to study specific numbers of lung cancer cases.

Risk of lung cancer versus measured radon concentration

After we stratified for study, age, sex, region of residence, and smoking the risk of lung cancer increased by 8.4% (95% confidence interval 3.0% to 15.8%; $P=0.0007$) per 100 Bq/m^3 increase in measured radon concentration. We stratified for smoking by first subdividing the individuals into seven categories (lifelong non-smokers, current smokers of <15, 15-24, or ≥ 25 cigarettes a day, ex-smokers for <10 years or ≥ 10 years, and others) and then further subdividing each group of current smokers by the age at which they started smoking (<15, 15-17, 18-20, or ≥ 21 years or unknown) and each group of ex-smokers by amount previously smoked (<15, 15-24, or ≥ 25 a day or unknown). If smoking had been omitted from the stratification, the risk of lung cancer would have increased by only 2.3% per 100 Bq/m^3 increase in measured radon, and if it had been included with only seven categories, the estimated increase would have been 5.2%. In all subsequent analyses we used the full smoking stratification.

The proportionate increase in risk was not strongly influenced by any one study. When we re-estimated the risk omitting each study in turn, it changed at most by a fifth. Nor did it vary substantially according to the period used to calculate radon exposures. The above analyses relate to measured radon concentrations 5-34 years earlier. Measured radon in periods 5-14, 15-24, and 25-34 years earlier were highly correlated, so the relation of risk to radon in each of these three periods was similar to that for the entire period (7.5%, 7.6%, and 6.6%, respectively). When we considered radon concentrations throughout the period 5-34 years earlier but with contributions from periods 5-14, 15-24, and 25-34 years earlier weighted in proportions 1.0:0.75:0.50, as suggested by the miners' studies,[2] the risk was unaltered, at 8.4% per 100 Bq/m^3 of measured radon.

When we subdivided study participants according to seven categories of measured radon (table 2), the results were consistent with a linear dose-response relation (fig 1). There was no significant curvature of the best fitting regression line, and no point differed significantly from this line. The linear relation remained significant even when we limited analysis to measured concentrations <200 Bq/m^3 ($P=0.04$). When we compared

BMJ: first published as 10.1136/bmj.38308.477650.63 on 21 December 2004. Downloaded from http://www.bmj.com/ on 29 March 2024 by guest. Protected by copyright.

Table 2 Relative risk of lung cancer by radon concentration (Bq/m³) in homes 5-34 years previously

Range of measured values	Mean (Bq/m³)		No of lung cancer cases/controls	Relative risk (95% floated CI)
	Measured values	Estimated usual values		
<25	17	21	566/1474	1.00 (0.87 to 1.15)
25-49	39	42	1999/3905	1.06 (0.98 to 1.15)
50-99	71	69	2618/5033	1.03 (0.96 to 1.10)
100-199	136	119	1296/2247	1.20 (1.08 to 1.32)
200-399	273	236	434/936	1.18 (0.99 to 1.42)
400-799	542	433	169/498	1.43 (1.06 to 1.92)
≥800	1204	678	66/115	2.02 (1.24 to 3.31)
Total	104/97*	90/86*	7148/14 208	—

*Cases/controls. Weighted average for controls, with weights proportional to study specific numbers of cases. Note that as random variation in measured values is approximately logarithmic (so measurement twice as big as usual value is about as likely as measurement half as big as usual value), means of measured values slightly exceed means of estimated usual values.

individuals with measured radon 100-199 Bq/m³ (mean 136 Bq/m³) versus those with measured radon <100 Bq/m³ (mean 52 Bq/m³) the relative risk was 1.20 (95% confidence interval 1.03 to 1.30; P=0.01). Models with no effect up to a "threshold" dose and then a linear effect did not fit significantly better than a linear effect with no threshold; in such models the upper 95% confidence limit for a possible threshold was 150 Bq/m³ measured radon.

Effect modification

There was no good evidence that the proportionate increase in lung cancer risk per 100 Bq/m³ measured radon differed by study (P=0.94), age (P=0.93), sex (P=0.19), or smoking status (P=0.98) (fig 2). We rejected a model in which the combined effects of radon and smoking were additive (P=0.05). When we considered lifelong non-smokers separately the increase in risk per 100 Bq/m³ was 10.6% (0.3% to 28.0%), and there was no evidence that it varied according to age, sex, or smoking status of the individual's spouse (P=0.46, 0.19, and 0.18, respectively).

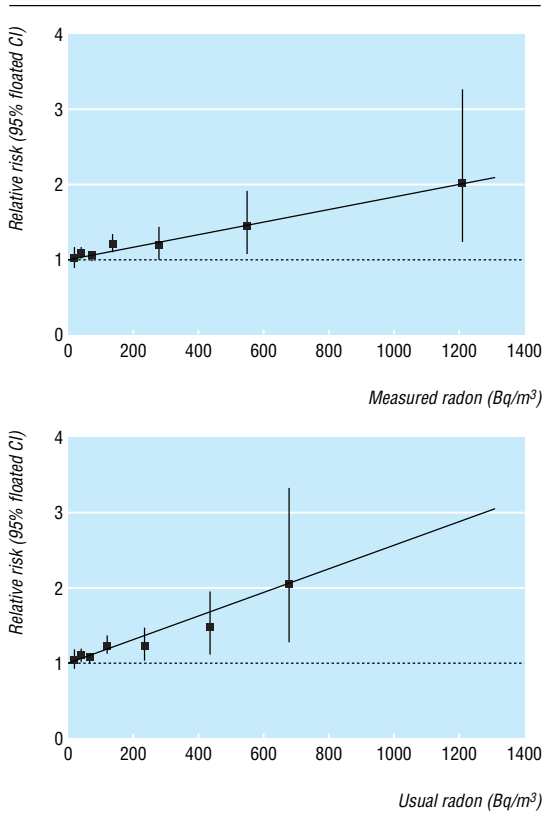


Fig 1 Relative risk of lung cancer according to measured residential radon concentration and usual residential radon concentration, with best fitting straight lines (risks are relative to that at 0 Bq/m³)

Microscopic confirmation of the diagnosis of lung cancer was available for 6310 individuals. The variation between the dose-response relations for the four histological types, as classified by the original studies, did not reach significance (P=0.07, fig 2). The increase in risk per 100 Bq/m³ measured radon, however, was 31.2% (12.8% to 60.6%) for small cell lung cancer, while for all other histological types combined it was 2.6% (<0% to 10.2%) (P=0.03 for difference), in accordance with the steeper dose-response relation reported for small cell cancer in early studies of miners exposed to radon.[2]

Allowance for random uncertainties in estimates of radon exposure

Measurements of radon concentrations in individuals' homes during the period 5-34 years previously are subject to substantial uncertainty. This uncertainty is not symmetrical. For example, if the true average long term concentration that an individual was exposed to was actually 300 Bq/m³, then the measured value for that individual could, by chance, be 500 too high (that is, 800 Bq/m³), especially if it depended on measurements in only one or two homes, but it could not be 500 too low. Detailed investigation of all available data concerning the variability in radon concentrations when the same house was measured in two different years suggests that, for most individuals with measured levels above 800 Bq/m³, the measured value was substantially higher than the usual or true long term average value.[7] Hence, although in the group with measured radon concentrations above 800 Bq/m³ the mean of the measured concentrations was 1204 Bq/m³, the estimated mean of their usual radon concentrations was only 678 Bq/m³ (table 2). If the mean usual radon concentration in this highly exposed group is only about half the mean measured value, then the slope of the line of risk versus usual radon concentration becomes about twice as steep as that of the line of risk versus measured radon concentration. When we re-estimated the risk of lung cancer, correcting for random uncertainties in measuring radon concentrations, it increased to 16% (5% to 31%) per 100 Bq/m³ usual radon. The dose-response relation with usual radon was consistent with a linear model (fig 1). Again there was no evidence that the risk per 100 Bq/m³ differed according to age, sex, or smoking.[7]

Combined effect of smoking and radon on absolute risk of lung cancer

For current smokers of 15-24 cigarettes a day the risk of lung cancer relative to that in lifelong non-smokers was 25.8 (21.3 to 31.2) for men in all 13 studies combined (after stratification by study, age, and region). Therefore, similarity of the relative risk between smokers and lifelong non-smokers would imply

BMJ: first published as 10.1136/bmj.38308.477650.63 on 21 December 2004. Downloaded from http://www.bmj.com/ on 29 March 2024 by guest. Protected by copyright.

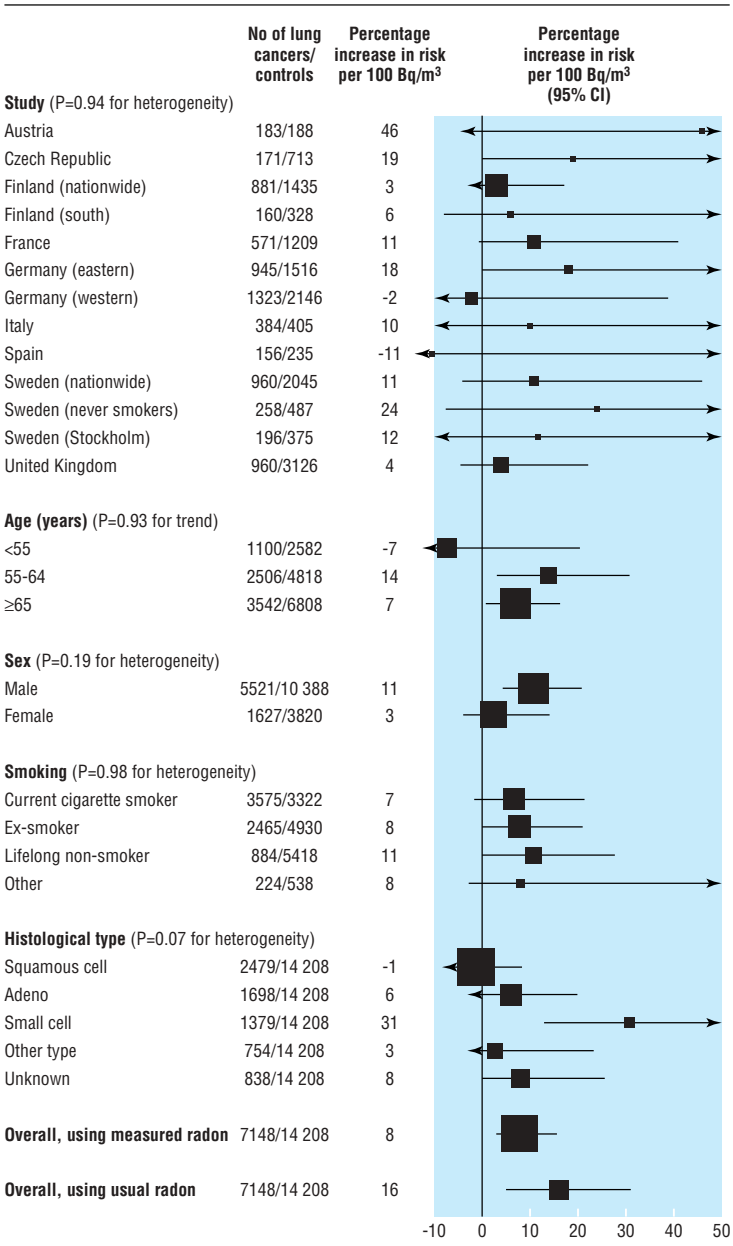


Fig 2 Percentage increase in risk of lung cancer per 100 Bq/m^3 increase in measured radon concentration by study, age, sex, smoking, and histological type. Squares have areas inversely proportional to the square of the standard error of the percentage increase. For the Spanish study, the present non-significantly negative estimate differs from a previously published positive estimate based on quartiles of radon distribution.[16] The negative estimate, based on individual radon concentrations, is dominated by three cases and 17 controls with measured radon ≥400 Bq/m^3

substantial differences in absolute risk per 100 Bq/m^3. If the risk of lung cancer increases by about 16% per 100 Bq/m^3 usual radon, regardless of smoking status, then at usual radon levels of 0, 100, 400, and 800 Bq/m^3, respectively, cumulative absolute risks of lung cancer by age 75 years would be 0.41%, 0.47%, 0.67%, and 0.93% in lifelong non-smokers and 10.1%, 11.6%, 16.0%, and 21.6% in cigarette smokers (fig 3).

Discussion

We were able to assess directly the risks from residential radon because our study involved large numbers of individuals with lung cancer and large numbers of unaffected individuals, all with detailed smoking histories. People with higher residential radon concentrations tended to smoke less, so that assessment of the magnitude of the risk associated with radon required detailed stratification for smoking history including amount smoked and age for current smokers, and years since stopping smoking and amount smoked for ex-smokers. Such detailed stratification has not previously been possible. Correction for the bias introduced by random uncertainties in the estimation of individual residential radon concentrations was also important.

After stratification for smoking there was strong evidence of an association between residential radon and lung cancer. The dose-response relation seemed linear with no evidence of a threshold, and a significant relation remained even among those whose measured radon concentrations were below 200 Bq/m^3.

BMJ: first published as 10.1136/bmj.38308.477650.63 on 21 December 2004. Downloaded from http://www.bmj.com/ on 29 March 2024 by guest. Protected by copyright.

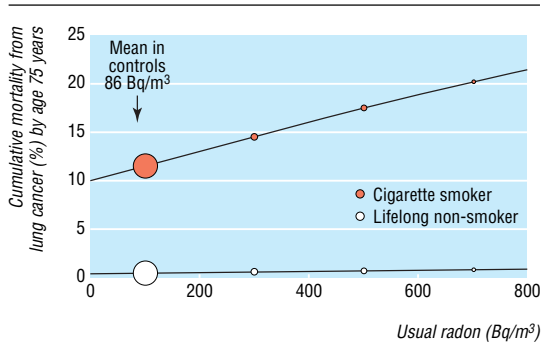


Fig 3 Cumulative absolute risk of death from lung cancer by age 75 years versus usual radon concentration at home for cigarette smokers and lifelong non-smokers. Plotted values calculated using relative risks for smoking from men in all studies combined, and absolute risks in lifelong non-smokers from US data for men and women combined.[20] Areas of circles proportional to numbers of controls with usual radon levels in ranges <200, 200-399, 400-599, and ≥600 Bq/m³

Correction for measurement error

After we corrected for random uncertainties in the assessment of radon concentrations, the dose-response relation in this study remained linear but nearly doubled in strength, to 16% (5% to 31%) per 100 Bq/m³. The magnitude of the correction is approximate as data on the variability between repeated measurements made in the same dwelling in different years are limited, but substantial correction is certainly necessary. There are also random errors in the assessment of smoking, and, if it had been possible to adjust for them, we would expect this to increase further the estimated effect of radon as there is negative confounding between smoking and radon. Radon concentrations within a home vary from room to room and so the actual radon concentration relevant to an individual will also vary, depending on the amount of time spent in different rooms. This is an additional source of random uncertainty and, if it could be taken into account, the estimated effect of radon could increase still further.

Our study was based on measurements of radon gas made in the recent past. Any systematic increase in radon concentrations over recent decades due, say, to increased energy efficiency would be a further source of dilution in our present risk estimates. Techniques to estimate historical radon concentrations through measurements of accumulated radioactive damage to the surfaces of glass objects that have been in the home for many years are being developed and may help to overcome this, but the uncertainties and biases associated with these techniques, especially in the presence of environmental tobacco smoke, are not fully understood.

Comparison with other studies of radon

Before correction for random uncertainties, the increased risk of lung cancer of 8% (3% to 16%) per 100 Bq/m³ in these European studies was consistent with that of 11% (0% to 28%) found in a recent combined analysis of North American studies.[21] The European collaboration, however, has greater power and more extreme statistical significance because it involves twice as many cases of lung cancer and higher radon concentrations (10% of measured values were >200 Bq/m³ versus 5% in the North American studies). Our results are also consistent with the pooled results of two Chinese studies[22] and with a meta-analysis of the published results of 17 studies, which, however, found marked heterogeneity between the different publications.[23] This heterogeneity disappeared in our analysis, in which data on each separate individual were collated centrally and analysed with uniform methods.

An analysis of miners exposed to concentrations below 0.5 "working levels" (approximately equivalent to 4600 Bq/m³ radon gas in the home) suggested risks were 19-30% per 100 Bq/m³, without correction for the effect of uncertainties in the assessment of radon exposures.[24] These estimates are higher than, but compatible with, the present estimate of 16% (5% to 31%).

Absolute hazard of radon for smokers and non-smokers

If the proportionate increases in risk per unit exposure are approximately independent of smoking history then, as lung cancer is much commoner in cigarette smokers than in lifelong non-smokers, radon poses a much greater absolute hazard to cigarette smokers, and to recent ex-smokers, than to lifelong non-smokers.

We have shown that residential radon produces substantial hazards, particularly among smokers, even at concentrations below the action levels currently recommended in many countries of a few hundred Bq/m³. The 2000 report from the United Nations Scientific Committee on the Effects of Atomic Radiation provided estimates of mean radon concentrations in dwellings for 29 European countries, with a population weighted average of 59 Bq/m³.[1] If this is approximately correct, and if the excess risk of lung cancer is about 16% per 100 Bq/m³ throughout a wide range of exposure levels, then radon in homes currently accounts for about 9% of the deaths from lung cancer and hence 2% of all cancer deaths in Europe. In most countries residential radon concentrations vary widely, with levels in most homes well below the national average but levels in a minority of homes several times higher than the national average. High radon concentrations can be reduced in existing houses at moderate cost, and low concentrations can usually be achieved at reasonable or low cost when new buildings are constructed.

What is already known on this topic

Exposure to the natural radioactive gas radon and its disintegration products can cause lung cancer

Exposure to radon gas in the home accounts for about half of all non-medical exposure to ionising radiation

High radon concentrations can be reduced in existing houses at moderate cost, and low concentrations can usually be ensured in new buildings at reasonable or low cost

What this study adds

After detailed stratification for smoking, there was strong evidence of an association between the radon concentration at home and lung cancer

The dose-response relation seemed to be linear, with no evidence of a threshold dose, and there was a significant dose-response relation even below currently recommended action levels

The absolute risk to smokers and recent ex-smokers was much greater than to lifelong non-smokers

Radon in the home accounts for about 9% of deaths from lung cancer and about 2% of all deaths from cancer in Europe

BMJ: first published as 10.1136/bmj.38308.477650.63 on 21 December 2004. Downloaded from http://www.bmj.com/ on 29 March 2024 by guest. Protected by copyright.

This paper is dedicated to the memory of Olav Axelson (1937-2004), who published the first study on radon in homes and lung cancer in the *Scandinavian Journal of Work, Environment and Health* in 1979. We thank the staff and participants in the collaborating studies. Richard Peto and Jon Miles provided helpful discussions during preparation of this paper, Gary Whitlock commented on a draft version, and Tom Fearn and David Cox provided helpful comments on the statistical methods.

Contributors: All authors were responsible for the design of this collaboration. The data for the component studies were the responsibilities of WO, LK, ASR, MK, HEW (Austria); . *Czech Republic:* LT (Czech Republic); AA, IM, MH (Finland nationwide); ER, IM, MH (Finland south); HB, MT (France); MK, ASR, IH, LK, HEW (Germany eastern); LK, MK, HEW (Germany western); FB, FF (Italy); GP, FL, RF (Sweden nationwide); FL, GP, RF (Sweden never smokers); GP (Sweden Stockholm); JMB-D, AR-R (Spain); SD, HD, DH, EW, RD (United Kingdom). CM coordinated the European Commission grant. DH, HD, EW, and SD collated the data for all studies in Oxford. The analysis was conducted and the report prepared by SD, DH, and RD with input from all other authors. SD, DH, and RD are guarantors.

Funding: Cancer Research UK (grants to Clinical Trial Service Unit and Cancer Epidemiology Unit) and the European Commission (contract FIGH-CT1999-00008). The funding sources had no role in study design, data collection, data analysis, data interpretation, the writing of the report, or the decision to submit the paper for publication.

Competing interests: None declared.

Ethical approval: Appropriate ethical committee approval was obtained for each study.

1 United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and Effects of Ionizing Radiation. UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. Vol I: Sources.* New York: United Nations, 2000.
2 National Research Council. *Committee on health risks of exposure to radon (BEIR VI). Health effects of exposure to radon.* Washington, DC: National Academy Press, 1999.
3 International Agency for Research on Cancer. *IARC monographs on the evaluation of carcinogenic risks to humans. Vol 78. Ionizing radiation. Part 2: Some internally deposited radionuclides.* Lyons: IARC, 2001.
4 Puskin JS. Smoking as a confounder in ecologic correlations of cancer mortality rates with average county radon levels. *Health Physics* 2003;84:526-32.
5 Heid IM, Schaffrath Rosario A, Kreienbrock L, Küchenhoff H, Wichmann HE. The impact of measurement error on studies on lung cancer and residential radon exposure in Germany. *J Toxicol Environ Health* (in press).
6 Darby S, Whitley E, Silcocks P, Thakrar B, Green M, Lomas P, et al. Risk of lung cancer associated with residential radon exposure in south-west England: a case-control study. *Br J Cancer* 1998;78:394-408.
7 Darby S, Hill D, Deo H , Auvinen A, Barros-Dios JM, Baysson H, et al. Residential radon and lung cancer: detailed results of a collaborative analysis of individual data on 7,148 subjects with lung cancer and 14, 208 subjects without lung cancer from 13 epidemiological studies in Europe. *Scand J Work Environ Health* (in press).
8 Lagarde F, Pershagen G, Åkerblom G, Axelson O, Bäverstam U, Damber L, et al. Residential radon and lung cancer in Sweden: risk analysis accounting for random error in the exposure assessment. *Health Phys* 1997;72:269-76.
9 Oberaigner W, Kreienbrock L, Schaffrath Rosario A, Kreuzer M, Wellmann J, Lerrer G, et al. *Radon und Lungenkrebs im Bezirk Imst/Österreich. Fortschritte in der Umweltmedizin.* Landsberg am Lech: Ecomed Verlagsgesellschaft, 2002.
10 Tomášek L, Müller T, Kunz E, Heribanová A, Matzner J, Plaček V, et al. Study of lung cancer and residential radon in the Czech Republic. *Cent Eur J Public Health* 2001;9:150-3.
11 Auvinen A, Mäkeläinen I, Hakama M, Castrén O, Pukkala E, Reisbacka H, et al. Indoor radon exposure and risk of lung cancer: a nested case-control study in Finland. *J Natl Cancer Inst* 1996;88:966-72 (plus erratum 1998;90:401-02).
12 Ruosteenoja E, Mäkeläinen I, Rytömaa T, Hakulinen T, Hakama M. Radon and lung cancer in Finland. *Health Phys* 1996;71:185-9.
13 Baysson H, Tirmarche M, Tymen G, Gouva S, Caillaud D, Artus JC, et al. Case-control study on lung cancer and indoor radon in France. *Epidemiology* 2004;15:709-16.
14 Wichmann HE, Shaffrath Rosario A, Heid IM, Kreuzer M, Heinrich J, Kreienbrock L. Lung cancer risk due to residential radon in a pooled and extended analysis of studies in Germany. *Health Physics* (in press).
15 Bochicchio F, Forastiere F, Farchi S, Quarto M, Axelson A. Residential radon exposure, diet and lung cancer: a case-control study in a Mediterranean region. *Int J Cancer* (in press).
16 Barros-Dios JM, Barreiro MA, Ruano-Ravina A, Figueiras A. Exposure to residential radon and lung cancer in Spain: a population-based case-control study. *Am J Epidemiol* 2002;156:548-55.
17 Pershagen G, Åkerblom G, Axelson O, Clavensjö B, Damber L, Desai G, et al. Residential radon exposure and lung cancer in Sweden. *N Engl J Med* 1994;330:159-64.
18 Lagarde F, Axelsson G, Damber L, Mellander H, Nyberg F, Pershagen G. Residential radon and lung cancer among never-smokers in Sweden. *Epidemiology* 2001;12:396-404.
19 Pershagen G, Liang Z-H, Hrubec Z, Svensson C, Boice Jr JD. Residential radon exposure and lung cancer in Swedish women. *Health Phys* 1992;63:179-86.
20 Peto R, Lopez A, Boreham J, Thun M, Heath C. Mortality from tobacco in developed countries: indirect estimation from national vital statistics. *Lancet* 1992;339:1268-78.
21 Krewski D, Lubin JH, Zielinski JM, Alavanja M, Catalan VS, Field RW, et al. A combined analysis of North American case-control studies of residential radon and lung cancer. *Epidemiology* (in press).
22 Lubin JH, Wang ZY, Boice JD Jr, Xu ZY, Blot WJ, Wang LD, et al. Risk of lung cancer and residential radon in China: pooled results of two studies. *Int J Cancer* 2004;109:132-7.
23 Pavia M, Bianco A, Pileggi C, Angelillo IF. Meta-analysis of residential exposure to radon gas and lung cancer. *Bull World Health Organ* 2003;81:732-8.
24 Lubin JH, Tomášek L, Edling C, Hornung RW, Howe G, Kunz E, et al. Estimating lung cancer mortality from residential radon using data for low exposures of miners. *Radiat Res* 1997;147:126-34.

(Accepted 2 November 2004)

doi 10.1136/bmj.38308.477650.63

Clinical Trials Service Unit and Epidemiological Studies Unit, Radcliffe Infirmary, Oxford OX2 6HE
S Darby *professor of medical statistics*
D Hill *statistician*
R Doll *emeritus professor of medicine*

School of Public Health, University of Tampere, Tampere, Finland
A Auvinen *professor of epidemiology*

Area of Preventive Medicine and Public Health, University of Santiago de Compostela, Spain
J M Barros-Dios *professor of epidemiology*
A Ruano-Ravina *professor of epidemiology*

Institut de Radioprotection et de Sûreté Nucléaire, Direction de la Radioprotection de l'Homme, Service de Radiobiologie et d'Epidémiologie, Fontenay-aux-Roses Cedex, France
H Baysson *statistician*
M Tirmarche *epidemiologist*

Unit of Radioactivity and its Health Effects, Department of Technology and Health, Italian National Institute of Health, Rome, Italy
F Bochicchio *senior researcher*

Department of Applied Statistics, University of Reading, Reading RG6 2AL
H Deo *statistician*

Swedish Radiation Protection Authority, SE-171 16, Stockholm, Sweden
R Falk *principal scientist*

Department of Epidemiology, Rome E Health Authority, Rome, Italy
F Forastiere *professor of epidemiology*

Finnish Cancer Registry, Helsinki, Finland
M Hakama *professor of epidemiology*

Institute of Epidemiology, GSF Research Centre for Environment and Health, Neuherberg, Germany
I Heid *statistician*
A Schaffrath Rosario *statistician*
H-E Wichmann *professor of epidemiology*

Institute of Biometry, Epidemiology and Information Processing, University of Veterinary Medicine, Hannover, Germany
L Kreienbrock *professor of statistics*

Department of Radiation Protection and Health, Federal Office for Radiation Protection, Neuherberg, Germany
M Kreuzer *epidemiologist*

Institute of Environmental Medicine, Karolinska Institute, S-171 77, Stockholm, Sweden
F Lagarde *statistician*
G Pershagen *professor of environmental medicine*

STUK-Radiation and Nuclear Safety Authority, Helsinki, Finland
I Mäkeläinen *health physicist*
E Ruosteenoja *scientist*

National Radiological Protection Board, Chilton, Didcot OX11 0RQ
C Muirhead *statistician*

Tumorregister Tirol, Innsbruck, Austria
W Oberaigner *epidemiologist*

Epidemiology Unit, National Radiation Protection Institute, Prague, Czech Republic
L Tomášek *statistician*

Department of Social Medicine, University of Bristol, Bristol BS8 2PR
E Whitley *visiting lecturer in medical statistics*

Correspondence to: S Darby sarah.darby@ctsu.ox.ac.uk

BMJ: first published as 10.1136/bmj.38308.477650.63 on 21 December 2004. Downloaded from http://www.bmj.com/ on 29 March 2024 by guest. Protected by copyright.