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

See bmj.com for full details for all authors

Clinical Trials Service Unit and Epidemiological Studies Unit, Radcliffe Infirmary, Oxford OX2 6HE

S Darby
professor of medical statistics

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

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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 homes 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 decay of the uranium-238 present throughout the earth's crust. It has a half life of four days, allowing it to diffuse through soil and into 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, 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 is uncertain but suggests that residential radon, which involves lower exposure to many more 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 low cost in new buildings—for example, by installing a radon proof barrier at ground level.

Studies to estimate directly the risk of lung cancer associated with residential radon exposure have been conducted in many European countries. Individually none has 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] 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 included over 150 people with lung cancer and 150

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controls, incorporated detailed smoking histories, and sought radon measurements[5] in homes where these individuals had lived during the past 15 years or more. Information was compiled for each person in a common format, and radon measurements were expressed in becquerels (Bq) (radon disintegrations per second) per cubic metre of household air.

Based on the miners' studies, we assumed that the relevant period of radon exposure was the 30 years ending five years before the diagnosis of lung cancer or before a corresponding date for the controls. The available radon measurements covered 23 years on average. For homes where radon measurements were unobtainable, we estimated the concentration from measurements in the homes of controls. 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.

Statistical methods

We assessed the association between radon and lung cancer in two ways. Firstly, a model was fitted in which the additional risk of lung cancer was proportional to measured radon. Secondly, we subdivided cases and controls by categories of measured radon and plotted relative risks across different categories against estimated mean levels in those categories. In both analyses, confounding was controlled through stratification.

Radon measurements made in the same home but in different years show considerable random variability. Further random uncertainty arises as radon could not always be measured and was estimated indirectly. Both types of uncertainty lead to "regression dilution," whereby the relation of risk to measured radon is weaker than the relation to "usual" (that is, true long term average) radon.[6 7] We calculated dose-response relations both with and without correction for this, and estimated a time-weighted average usual radon concentration for each individual.

Results

Our analysis included 7148 people with lung cancer and 14 208 controls. For lung cancer cases the mean measured radon concentration was 104 Bq/m^3 while for controls the corresponding average was 97 Bq/m^3 (table). Among controls, the percentage who were lifelong non-smokers increased with radon concentration (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).

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[8]	1983	267	130
Czech Republic[9]	1981	528	493
Finland (nationwide)[10]	1989	104	103
Finland (south)[11]	1982	221	212
France[12]	1995	138	131
Germany (eastern)[13]	1994	78	74
Germany (western)[13]	1993	49	51
Italy[14]	1995	113	102
Spain[15]	1993	123	137
Sweden (nationwide)[16]	1982	99	94
Sweden (never smokers)[17]	1990	79	72
Sweden (Stockholm)[18]	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 with weights proportional to the length of time the individual had lived in each.
†Weighted average, with weights proportional to study specific numbers of lung cancer cases.

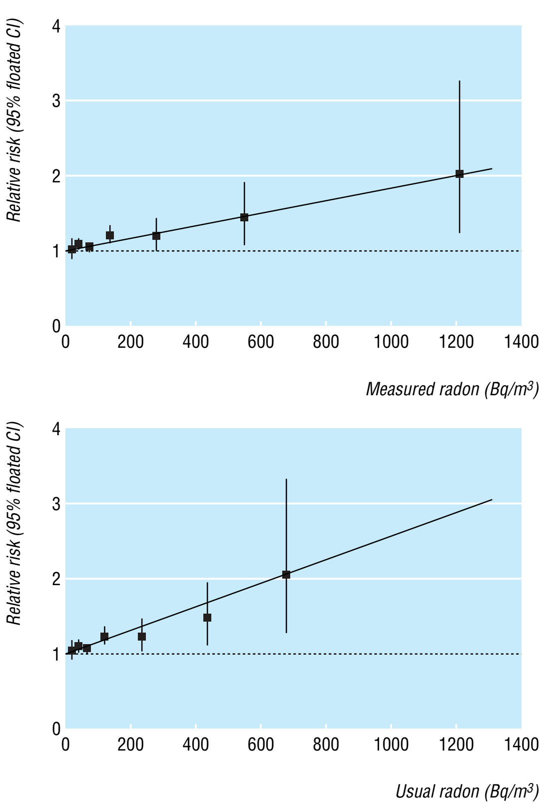

Fig 1 Relative risk of lung cancer according to measured residential radon concentration and usual residential radon concentration, with best fitting straight lines (risks are relative to that at 0 Bq/m^3)

Risk of lung cancer versus measured radon concentration

After stratification for study, age, sex, region of residence, and for 25 categories of 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. If smoking had been omitted from the stratification, the risk would have increased by only 2.3% per 100 Bq/m^3, and if it had been included with only seven categories, the estimated increase would have been 5.2%. In subsequent analyses we used the full smoking stratification.

When we subdivided study participants according to categories of measured radon, the results were consistent with a linear dose-response relation (fig 1). The linear relation remained significant even when we limited the analysis to measured concentrations <200 Bq/m^3 ($P=0.04$).

Effect modification

The proportionate increase in lung cancer risk per 100 Bq/m^3 measured radon did not differ significantly by study, age, sex, or smoking status. 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/m^3 was 10.6% (0.3% to 28.0%), and did not differ significantly by age, sex, or smoking status of the individual's spouse.

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 300 Bq/m^3, then the measured value could, by chance, be 500 too high (at 800 Bq/m^3), but not 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/m^3, the measured value was substantially higher than the usual or true long term average value.[5] Hence, although in the group with measured radon above 800 Bq/m^3 the mean of the measured concentrations was 1204 Bq/m^3, the estimated mean of their usual radon concentrations was only 678 Bq/m^3. If the mean usual radon in this highly exposed group is about half the mean measured value, then the slope of the relationship versus usual radon becomes about twice as steep as that of the relationship versus measured radon. When we re-estimated the risk of lung cancer, correcting for random uncertainties in measuring radon, it increased to 16% (5% to 31%) per 100 Bq/m^3 usual radon. The dose-response relation with usual radon was consistent with a linear model (fig 1). The risk per 100 Bq/m^3 did not differ significantly by age, sex, or smoking.[5]

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. Therefore, similarity of the relative risk between smokers and non-smokers would imply 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 2).

Discussion

We were able to assess directly the risks from residential radon because our study involved large numbers of individuals with lung cancer and controls, 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. There was strong evidence of an association between residential radon and lung cancer. The dose-response relation seemed linear, and a significant relation remained even among those with measured radon below 200 Bq/m^3. Correction for the bias introduced by random uncertainties in the estimation of individual residential radon concentrations was also important, nearly doubling the strength of the dose-response relation to 16% (5% to 31%) per 100 Bq/m^3. The magnitude of the correction is approximate, as data on the variability between repeated measurements made in the same dwelling in different years are scarce, but substantial correction is certainly necessary.

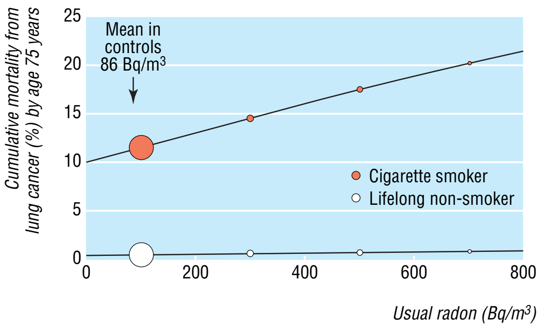

Fig 2 Cumulative absolute risk of death from lung cancer by age 75 years versus usual radon concentration at home for cigarette smokers and lifelong non-smokers. Plotted values calculated using relative risks for smoking from men in all studies combined, and absolute risks in lifelong non-smokers from US data for men and women combined.[5] Areas of circles proportional to numbers of controls with usual radon levels in ranges <200, 200-399, 400-599, and ≥600 Bq/m^3

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/m^3 in these European studies was consistent with that of 11% (0% to 28%) found in a recent combined analysis of North American studies.[19] Our results are also consistent with the pooled results of two Chinese studies[20] and with a meta-analysis of the published results of 17 studies, which, however, found marked heterogeneity between the different publications.[21] 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/m^3 radon gas in the home) suggested risks were 19-30% per 100 Bq/m^3, without correction for the effect of uncertainties in the assessment of radon exposures.[22] 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

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/m^3. 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/m^3.[1] If this is approximately correct, and if the excess risk of lung cancer is about 16% per 100 Bq/m^3, then radon in homes currently accounts for about 9% of the deaths from lung cancer

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

and hence 2% of all cancer deaths in Europe. In most countries radon concentrations vary widely, with levels in most homes below the national average but with levels in some homes several times above it. High radon concentrations can be reduced in existing houses at moderate cost, and low concentrations can usually be achieved at low cost in new buildings.

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.

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

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Science commentary: Radon blues

Geoff Watts

28 New End
Square, London
NW3 1LS
Geoff Watts
science editor, BMJ
geoff@
scileg.freeserve.co.uk

The publication of a new collaborative study of the effect of domestic radon on the risk of lung cancer is a reminder that this is a hazard to be taken seriously.[1] Of course, health campaigners will rightly respond that radon gas, the cause of just under a tenth of deaths from lung cancer, is hardly in the same league as tobacco. That said, as a carcinogen worth tackling it does have one great "virtue." Unlike the perilous ingredients in materials that we choose to smoke, the threat posed by radon can be greatly reduced or even eliminated without a painful reliance on willpower or on the exercise of self denial. Unfortunately, the extent to which even the relatively pain-free remedies for dealing with it are actually applied is less then impressive.

The appropriate course of action will depend on the construction of the building and the level of radon