Occup Environ Med 1998;**55**:52–58

Risks of silicosis in coalworkers exposed to unusual concentrations of respirable quartz

Brian G Miller, Suzanne Hagen, Richard G Love, Colin A Soutar, Hilary A Cowie, Malcolm W Kidd, Alastair Robertson

Abstract

***Objectives*—To describe the radiographic changes in coalworkers exposed to unusual concentrations of respirable quartz during the 1970s, and to relate these to exposure measurements.**

***Methods*—Men who had worked at one Scottish colliery during the 1970s were invited to a health survey. Chest radiographs were taken from 547 subjects. Classifications of these films under the International Labour Organisation (ILO) 1980 scheme were related, by logistic regression, to existing data on individual men's exposures to respirable dust and quartz.**

***Results*—Taking the median of the three readers' results on profusion of small opacities, 203 men (38%) showed progression of at least one profusion category on the 12 point scale, from the various 1970s surveys to the follow up in 1990–1. A total of 158 men (29%) had a profusion of at least 1/0, and 47 (8.6%) of at least 2/1 at the follow up survey. Large opacities were recorded as present by at least two readers for 14 (2.6%) of the men. Profusion of small opacities was strongly related to exposures experienced in the 1970s, and more strongly for quartz than for the non-quartz fraction of the dust. Estimates of risk are presented over the range of quartz exposures experienced.**

***Conclusions*—The quartz exposures experienced by some men at this colliery have caused considerable progression of radiographic abnormalities since exposure ended. The data accumulated offer opportunities for further more detailed analyses to inform debate on occupational limits for quartz exposures, both in collieries and in other industries where there is exposure to quartz in mixed dust.**

(*Occup Environ Med* 1998;**55**:52–58)

Keywords: silica; silicosis; coalworkers; exposure-response; quartz

Institute of Occupational Medicine, 8 Roxburgh Place, Edinburgh EH8 9SU, UK
B G Miller
S Hagen
R G Love
C A Soutar
H A Cowie
M W Kidd
A Robertson

Correspondence to:
Dr B Miller, Institute of Occupational Medicine, 8 Roxburgh Place, Edinburgh EH8 9SU, UK.

Accepted 17 July 1997

There is a shortage of reliable information on the risks of silicosis after exposure to respirable quartz, particularly as a component of respirable mixed dust. Epidemiological exposure-response studies so far[1–7] give widely disparate estimates of risk, almost certainly because of deficiencies in the exposure data,[8] much of which is poorly suited, or was never intended, for the reliable estimation of risks.

Some members of a colliery population were exposed, during a period in the 1970s, to unusually high concentrations of freshly cut quartz in mixed coalmine dust. The population's exposures to quartz dust had been measured in unique detail, for a substantial proportion of the men's working lives, and throughout the period when the critical exposures occurred. Health status was monitored at regular intervals while the population was exposed.

We report on the results of a follow up survey of the respiratory health of survivors from this population. We describe the radiographic abnormalities which have developed, some of them severe; derive exposure-response relations for the risks of developing the silicotic abnormalities; and calculate preliminary risk predictions.

THE COLLIERY

In the early 1950s the National Coal Board began the pneumoconiosis field research (PFR) programme, which has been the principal source of epidemiological data on coalworkers' pneumoconiosis in the United Kingdom. The programme of collection of research data lasted for over 30 years, and was based on regular examinations of the workforce at selected collieries, detailed descriptions of the wide range of working environments within those collieries, extensive dust sampling and compositional analysis throughout, and regular recording of the times each man spent working in those environments.

One particular Scottish colliery took part in a total of six medical surveys between 1954 and 1978. The prevalence of pneumoconiosis at the colliery during the research was low, reflecting the general Scottish experience. However, the medical officer who read and classified the radiographs taken at the sixth PFR survey in 1978 considered that 21 radiographs from the 623 taken showed unusually rapid progression of simple pneumoconiosis when compared with radiographs taken four years earlier from the same men at the fifth survey.

This finding spurred a small case-control study at this colliery.[9] Although based on only 21 case-control pairs, the results showed clear relations between the progression of pneumoconiosis and exposure to respirable coal mine dust, and in particular to the quartz part of that dust; and the radiological appearances of the cases had, in many respects, the appearance of silicosis. A more extensive investigation of radiological evidence from this colliery confirmed the results and showed that the association was strongest with the increased quartz exposures experienced in the 1970s.[10]

Table 1 Chronology of PFR surveys and intersurvey periods (ISPs)

Month	*PFR survey*	*Begins (ISP)*	*Approximate duration of ISP (y)*
Before surveys		ISP 0	Variable
Feb 1954	PFR 1	ISP 1	4
April 1958	PFR 2	ISP 2	6
Feb 1964	PFR 3	ISP 3	7
Dec 1970	PFR 4	ISP 4	4
Oct 1974	PFR 5	ISP 5	4
Nov 1978	PFR 6	ISP 6	> 2

Respirable coal mine dust normally contains a small proportion (usually <10%) of silica or silicates, mostly from dirtbands within the coal stratum. The source of the increased quartz exposures experienced here, however, was sandstone strata between which the coal lay. For a time in the 1970s, incursions of the coal getting machinery into these strata had been responsible for the emission of unusually large quantities of respirable quartz dust.

The aims of the study were: (*a*) to determine the current respiratory health of men exposed to unusually high concentrations of respirable quartz between about 1968 and 1980; and (*b*) to study the quantitative relations between history of exposure to respirable quartz in mixed coal mine dust and risk of chest radiographic abnormality.

Methods

STUDY POPULATION

The programme of PFR at the colliery began in 1954 and continued until the colliery closed in 1981. We refer throughout this report to PFR surveys and to the intersurvey periods (ISPs) between them, during which data on exposures were collected. Table 1 shows the rough chronology of these (the months given are those containing most of the several weeks which the surveys took to complete). We use the term "ISP 6" to cover the period from the 6th survey to the colliery's eventual closure, and "ISP 0" refers to any period spent employed in coalmining before PFR 1. Response rates were high, as was generally true of the PFR. Contemporary records of the surveys at this pit show that PFR 4 and PFR 5 were attended by 88% and 91% of the eligible population; and that these responses included 91% and 95% respectively of underground workers.

The study of Miller and Kinnear[10] was based on a detailed re-examination of the available chest radiographs for men who had attended any of the 4th, 5th, and 6th PFR surveys at the colliery, which took place in 1970, 1974, and 1978 respectively. This led to a study group of 1416 men, for whom a total of 2612 relevant radiographs were retrieved. The new follow up study was designed to trace as many as possible of the survivors from this group of 1416, and to invite them to participate in a medical survey similar to those of the PFR.

TRACING AND RECRUITMENT

The colliery closed in 1981, to be followed by almost all of the remaining British Coal collieries in Scotland. Therefore, the task faced was that of tracing men, few of whom would still be employed in the coal industry, and a proportion of whom would have retired or died in the intervening period. Addresses held were in many cases likely to be out of date. No single route of tracing and contacting these men presented itself, so several sources were used in turn.

Some of the men were members of an existing mortality cohort,[11] from which about 200 men were identified as already dead. Attempts were made to contact the remaining men, in several waves, with the Department of Social Security's letter forwarding service, British Coal's Pensions and Insurance Department, and local contacts by both letter and door to door enquiry. Of 1032 men not identified as dead, 156 were untraced or did not reply to any contact. Of 876 who replied, 711 agreed to be surveyed.

The bulk of the survey work was carried out from mid-November 1990 to the end of that year, with additional single weeks in January and April 1991. The total number of men surveyed was 551, including one man interviewed in hospital, and for whom a recent chest radiograph was available. Two men were omitted from analysis because of suspected misidentification, and a further two from whom chest radiographs were not taken.

SURVEY METHODS

The survey methods were based on those which had been used in the PFR research programme. Mobile survey units were sited adjacent to the former colliery. A full sized posteroanterior chest radiograph was taken from all but two men, and these were processed on site. An experienced clerk administered a questionnaire on smoking habits and occupational history since leaving the colliery. Measurements taken but not reported here included simple spirometry and a questionnaire on respiratory symptoms.

INTERPRETATION OF RADIOGRAPHS

Three physicians were recruited as epidemiological readers, each of whom had considerable experience of classifying pneumoconiotic abnormalities on chest radiographs. For each man, an envelope was prepared containing the radiograph from the 1990/91 follow up survey, plus any radiograph taken in the PFR 5 survey in 1974, or the PFR 6 survey in 1978, or both. If no such radiograph were available, one from the PFR 4 survey in 1970 was used. The reading protocol required the reader firstly to classify the follow up radiograph independently; then to compare the follow up with the earlier films and classify all of these, revising the reading for the follow up radiograph if the reader's opinion was altered by sight of the earlier film. All classifications were according to the International Labour Organisation (ILO) 1980 classification scheme.[12]

CALCULATION OF ESTIMATED EXPOSURES

Respirable dust concentrations were measured at the colliery from 1954 until its closure in 1981. Dust samples were analysed for quartz,

Table 2 Distribution of study population by age and smoking habits at follow up survey (values are number of men)

Smoking habits	Age at follow up survey (y) < 35	35-44	45-54	55-64	65-74	≥ 75	Total
Non-smokers	9	16	20	20	16	7	88
Ex-smokers	3	11	19	60	86	31	210
Current smokers	10	33	55	68	63	20	249
Total	22	60	94	148	165	58	547

kaolinite, and illite or mica with infrared spectrophotometry.[13]

Extensive dust concentration measurements were made, in a programme the design of which was based on many different occupational groups. Data from the colliery payroll systems, detailing which men had worked in which occupations and locations and for how long, were converted to the same occupational group system.

Individual respirable dust exposures were estimated for each worker, by cumulating the products of concentrations typical of the specific occupational groups and the time worked in those occupations.[14 15] With the proportions of constituent fractions of the dust, notably ash and quartz, it was possible similarly to calculate estimates of cumulative exposures to these constituents. For this study, separate estimates were made of exposures to respirable quartz, and (by subtraction) to the non-quartz fraction of respirable dust, for each of ISPs 3, 4, 5, and 6 (table 1). Exposures up to PFR 3 were combined for the whole of the period ISP 0+1+2.

Occupations held after leaving the pit, recorded on the occupational history forms, were assigned standardised occupation codes, and times spent in different kinds of colliery and non-colliery occupations were cumulated. As no concentration measurements were available for these periods, the times could not be converted to exposures.

STATISTICAL METHODS

Tabulations and summaries of the data, including those employed to check and validate the data after data entry, used the database management system SIR,[16] and the statistical packages BMDP[17] and Genstat.[18] Investigation of relations between radiological abnormalities (treated as present or absent) and exposure histories, adjusting for factors such as smoking habits, used logistic regression methods[19] in the statistical package Genstat.[18]

Further details of the study methodology are available in report form.[20]

Results

POPULATION SURVEYED

Table 2 summarises the ages and smoking habits of the 547 men with chest radiographs from the follow up survey. Ages at follow up ranged from 29 to 85 years, with a mean of almost 60 years, and 68% of the men were aged 55 years or older when surveyed. The pattern of smoking habits was broadly as expected in an older industrial population, with proportionally more non-smokers among the younger men, and most ex-smokers among the oldest men.

EXPOSURE TO RESPIRABLE DUST AND QUARTZ

During the 1970s, most coaling activity was centred on two seams. In the first (seam A), quarterly mean concentrations for all underground occupational groups between 1969 and its end in 1977 were <1 $mg.m^{-3}$, with <10% exceeding 0.3 $mg.m^{-3}$. In the other (seam B) the situation was very different. More than 10% of the quarterly mean concentrations were >1 $mg.m^{-3}$, with two means >10 $mg.m^{-3}$. Figure 1 shows the pattern of these increased concentrations with time, with the occupational groups distinguished by letter as listed. (Means based on <10 samples are not included.)

Examination of the data summarised in fig 1 showed that the periods with high quartz concentrations were characterised by high overall dust concentrations, and by exceptionally high proportions of quartz, up to a maximum of 60%, in the collected dust. In seam A, the proportion of quartz never exceeded 15%. The occupations affected in seam B were positioned either at the face or at its return end—that is, where the ventilating air had already passed over the coal face and become loaded with dust. Values for two other seams worked for shorter periods were similar to those for seam A.

Inspection of colliery environmental reports showed that the highest quartz exposures occurred during the working of three separate faces in seam B, between early 1971 and mid 1976. Coal measures in these faces were thinner than in earlier faces in this seam, and the roof and floor of each face were sandstone. The powered mining methods in use made incursions into the sandstone strata, causing unusually high concentrations of quartz.

Table 3 shows the results of combining these concentrations, and those for respirable non-quartz dust, with the records of time worked, to estimate individual exposures. These are summarised to show the number of men with

Table 3 Summary of estimated dust and quartz exposures calculated for men in study population

Intersurvey period (ISP)	Exposures to respirable non-quartz dust (ghm^{-3}) Number > 0	Mean	Max	Exposures to respirable quartz (ghm^{-3}) Mean	Max	Percentage quartz in respirable dust (%) Min	Mean	Max
ISP 0+1+2	304	26.4	128.5	1.33	7.00	0.4	4.8	7.6
ISP 3	502	13.4	35.1	1.38	5.79	1.8	7.7	17.5
ISP 4	519	7.1	27.8	0.95	7.89	2.4	8.6	29.4
ISP 5	440	5.1	21.7	0.70	4.73	1.6	9.1	26.6
ISP 6	370	1.1	12.6	0.12	1.62	0.0	7.3	16.1
ISP 0-6 incl	547	53.1	158.1	4.48	14.48	1.3	7.5	18.3
ISP 3-6 incl	547	26.7	78.7	3.15	14.40	1.3	8.5	19.3

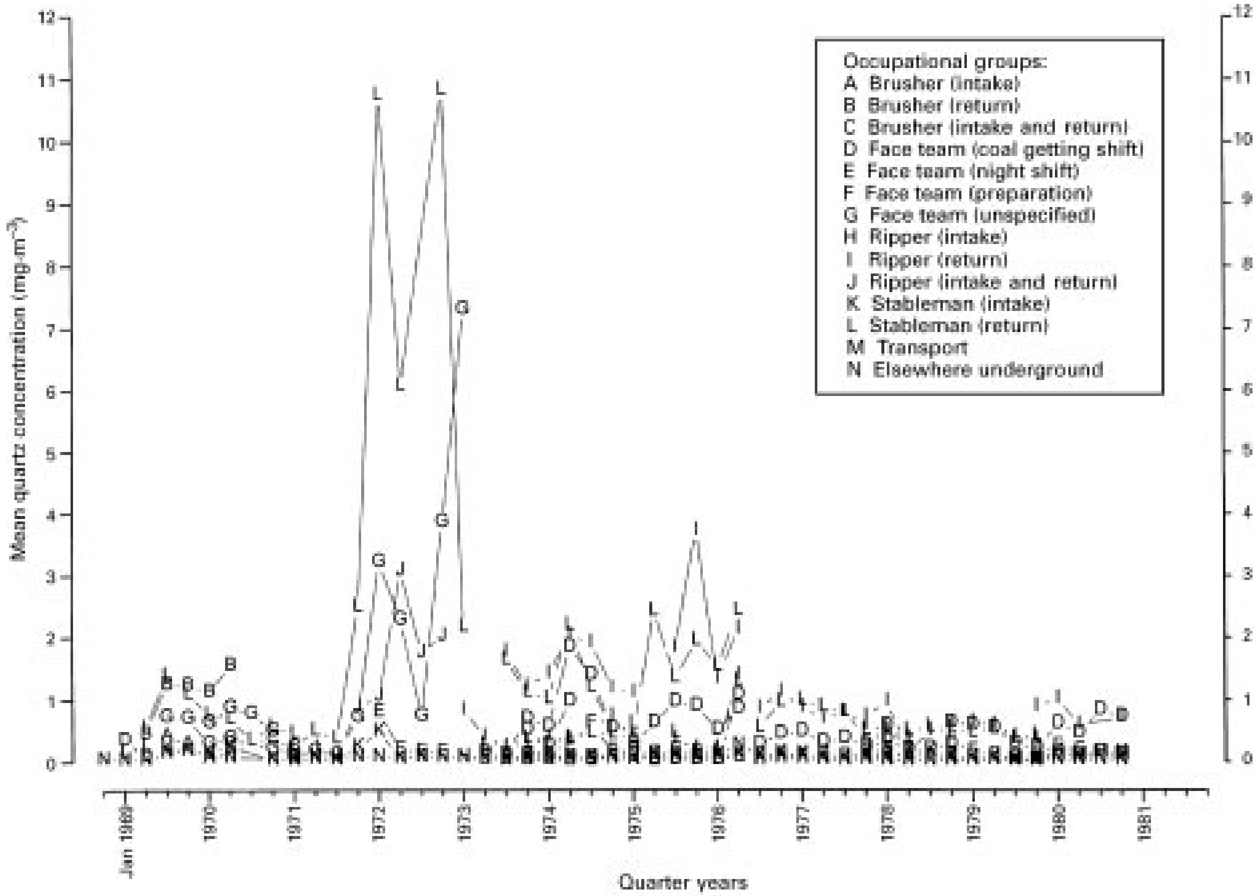

Figure 1 Estimated quarterly mean quartz concentrations in underground occupational groups in seam B.

non-zero times (and hence non-zero exposures) in each period—as not everyone was present in the colliery during every ISP—and the mean and maximum of the non-zero exposure estimates. The data are not differentiated by seam, as men worked on different seams at different times. The last columns of table 3 summarise the distribution of the ratio of estimated quartz exposure to estimated respirable dust exposure, and show that for some men their dust exposures had low average quartz content, whereas some men accumulated exposures consisting on average of almost 30% quartz.

Table 4 Comparison of median readings of small opacities from follow up radiograph and from last previous PFR radiograph (values are numbers of men)

Last PFR radiograph	Follow up radiograph 0/0	0/1	1/0	1/1	1/2	2/1	2/2	2/3	3/2	3/3	Total
0/0	317	54	40	25	4	4	4	3	2	1	454
0/1	—	11	12	12	4	4	4	2	1	—	50
1/0	—	1	3	3	2	5	5	2	—	—	21
1/1	—	—	—	1	3	1	1	2	—	—	8
1/2	—	—	—	—	2	—	—	—	—	—	2
2/1	—	—	—	—	—	—	3	—	—	—	3
2/2	—	—	—	—	—	—	2	—	—	—	2
2/3	—	—	—	—	—	—	—	—	—	—	0
3/2	—	—	—	—	—	—	—	—	—	—	0
3/3	—	—	—	—	—	—	—	—	—	—	0
Not found	5	1	—	—	—	—	—	1	—	—	7
Total	322	67	55	41	15	14	19	10	3	1	547

INCIDENCE AND PROGRESSION OF PNEUMOCONIOTIC ABNORMALITIES

Table 4 summarises the classifications of small opacities from the epidemiological readings of the follow up radiographs, based on the median of the opinions of the three readers. This is compared with the median result of their classifications of the most recent available PFR radiograph from any of the PFR surveys. Only one radiograph showed apparent slight regression from 1/0 to 0/1. Progression of one step was found in 75 cases (14%), and of two steps in a further 55 cases (10%). In 203 cases (38%) there was apparent progression of one or more steps, and in 128 cases (24%) progression of two or more steps.

There were 14 radiographs taken at follow up where at least two of the three readers recorded the presence of large opacities. Table 5 lists these, and compares the median category of large opacities at follow up with that for the most recent PFR radiograph. Also shown are the median profusions of small opacities for the same radiographs. There was no subject for

Table 5 Details of median readings for men classified by at least two readers as having large opacities on the follow up radiograph

Large opacities		*Small opacities*	
Last PFR radiograph	*Follow up radiograph*	*Last PFR radiograph*	*Follow up radiograph*
0	A	1/0	2/3
0	A	0/0	1/0
0	A	0/1	2/1
0	B	2/2	2/2
0	A	0/0	0/0
A	A	2/1	2/2
0	A	1/0	2/1
0	B	2/1	2/2
0	A	1/1	2/3
A	B	1/1	2/2
0	B	0/1	1/1
A	B	0/1	2/1
0	A	0/0	2/3
0	A	1/0	2/2

whom large opacities, based on the median reading, were absent on the follow up radiograph but present on the earlier film.

EXPOSURE-RESPONSE RELATIONS

Table 6 shows the distribution of the 47 men who, at follow up survey, had a profusion of median small opacities of 2/1 or greater (designated 2/1+), grouped by 10-year age groups and by quintiles of respirable quartz exposure cumulated from the start of ISP 3. There was a clear trend of increasing prevalence with increasing exposure, with 60% of the cases in the 20% of men with the highest exposures. The relation with age was less clear, although in the two lowest exposure categories the few cases were in older men.

The relation between risk of developing radiological abnormalities of profusion 2/1+ and exposure was investigated with logistic regression.[19] Many models were fitted with different combinations of exposure variables singly and in combination, with and without age and smoking habit, to aid interpretation. Only a few of the most informative models are shown here.

Table 7 shows some of the models fitted to the response 2/1+. Each column is a single model, and the coefficients present (not blank) show which variables were included in that model. The usefulness of adding a term to a model may be judged by treating the change in residual deviance as a χ^2 statistic, associated with the change in the number of residual degrees of freedom. Also, as all the variables are continuous predictors associated with a single degree of freedom, the ratio (shown in italics) of a coefficient to its standard error can be treated as an approximate z statistic, expected to follow the Gaussian (or normal) distribution.

Comparison of models A to D shows that the best single predictor of the risk of showing small opacities at a profusion of 2/1+ was exposure to respirable quartz. In general, the exposures for the periods ISP 3–6 were better predictors than those which also included ISPs 0–2. An example of this is seen by comparing model A with model E, when the results were similar but the ISP 3–6 quartz exposure was a slightly better predictor than that for ISP 0–6. Also, model F shows that, after fitting exposure to quartz in ISPs 0–6, adding the percentage quartz in this period significantly improved the model; whereas in model G, which restricted the exposure period to ISPs 3–6, there was no improvement from adding percentage quartz. Finally, model H shows that, with quartz exposure in the model, non-quartz dust gave no significant improvement, whereas the inclusion of quartz after non-quartz dust was highly significant. This is strong support for the conclusion that the abnormalities found are the result of the exposure to respirable quartz, rather than to the non-quartz content of the dust. An analogous model including exposures to respir-

Table 6 Prevalence of radiological abnormalities (values are numbers of men (n) grouped by age and by quintiles of cumulative exposure to respirable quartz, and numbers with small opacities profusion 2/1 or greater, and percentages)

Age at follow up	*Cumulative exposure to respirable quartz, ISP 3-6 (ghm^{-3})*															*All exposures*		
	0-0.37			*0.37-1.46*			*1.46-3.18*			*3.18-5.70*			*Over 5.70*					
	n	*2/1+*	*%*	*n*	*2/1+*	*%*	*n*	*2/1+*	*%*	*n*	*2/1+*	*%*	*n*	*2/1+*	*%*	*n*	*2/1+*	*%*
< 35	18	0	*0*	4	0	*0*	0	—	—	0	—	—	0	—	—	22	0	*0*
35-44	21	0	*0*	19	0	*0*	8	0	*0*	10	0	*0*	2	0	*0*	60	0	*0*
45-54	14	0	*0*	16	0	*0*	23	0	*0*	20	2	*10*	21	9	*43*	94	11	*12*
55-64	14	0	*0*	28	0	*0*	26	2	*8*	30	2	*7*	50	10	*20*	148	14	*9*
65-74	28	0	*0*	25	1	*4*	36	1	*3*	40	2	*5*	36	12	*33*	165	16	*10*
⩾ 75	14	1	*7*	18	2	*11*	16	2	*12*	10	1	*10*	0	—	—	58	6	*10*
All ages	109	1	*1*	110	3	*3*	109	5	*5*	110	7	*6*	109	31	*28*	547	47	*9*

Table 7 Results of logistic regression: positive response is median profusion of small opacities 2/1+; selected models showing relation with exposure variables

Variables in model	*Regression models*							
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*
Intercept	−4.32	−5.42	−4.77	−4.70	−4.28	−8.20	−4.24	−4.30
Quartz ISP 3-6	0.416 *7.83*						0.428 *4.51*	0.423 *3.88*
% Quartz ISP 3-6		0.295 *6.39*					−0.014 *0.16*	
Dust ISP 3-6			0.060 *7.16*					
Non-quartz dust ISP 3-6				0.066 *6.93*				−0.002 *0.08*
Quartz ISP 0-6					0.394 *7.50*	0.324 *5.45*		
% Quartz ISP 0-6						0.152 *2.81*		
Residual deviance	246.8	271.2	259.3	263.8	251.7	244.1	246.7	246.8
Degrees of freedom	545	545	545	545	545	544	544	544

Values are estimated regression coefficients with ratio of coefficient to SE in italics.

Table 8 Results of logistic regression on quartz exposures in separate ISPs

Variables in model	*Regression models* J	K	L	M
Intercept	−3.62	−3.90	−4.29	−4.64
Quartz ISP 0+1+2				0.204 *1.67*
Quartz ISP 3			0.333 *2.34*	0.284 *1.93*
Quartz ISP 4	0.847 *7.19*	0.666 *5.26*	0.487 *3.38*	0.517 *3.57*
Quartz ISP 5		0.482 *3.26*	0.497 *3.36*	0.578 *3.67*
Quartz ISP 6				
Residual deviance	259.2	249.5	244.3	241.7
Degrees of freedom	545	544	543	542

Values are estimated regression coefficients with ratio of coefficient to SE in italics.

able quartz and dust gave almost identical results and conclusions. Inclusion of smoking habits did not improve the fit of the regression models. As expected, the exposure variables were partly confounded with age, and the inclusion of age in the presence of quartz exposure fell short of the 5% significance level and made little difference to either the magnitude or the significance of the quartz exposure coefficient. We have chosen to present the models of table 7 without age effects.

Table 8 shows some additional models which distinguish further the effects of exposures experienced in different periods. The strongest relations were with quartz exposures in ISPs 4 and 5, followed by that in ISP 3, with a lower regression coefficient. Quartz exposure in ISPs 0+1+2 did not reach significance, although its magnitude seemed consistent with the effects from the other periods. Exposure in ISP 6 made no significant contribution (not shown). For some combinations of variables, age became a significant predictor; but the inclusion of age altered little the principal conclusions, and for consistency and ease of comparison we have shown here only models without age effects.

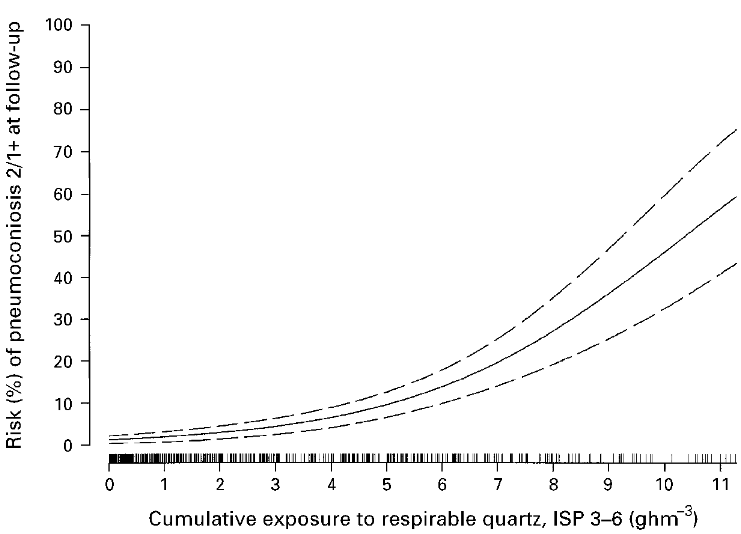

Figure 2 Predicted risks of small opacities 2/1+ at follow up, as a function of respirable quartz exposure in ISP 3–6. Dashed lines are approximate 95% CIs on predicted risk, calculated as 2 SE. Dashes on exposure axis show distribution of exposures in subjects surveyed.

We conclude that the evidence points strongly to the role of quartz exposures experienced between 1970 and 1978, in producing the radiological progression found in this population; and that some earlier quartz exposure may also have contributed to the risks.

Additional analyses (not shown here) showed that there was a strong association between radiological abnormalities at follow up and time spent working in the occupational groups known (fig 1) to have had the highest concentrations of respirable quartz.[20] There is scope for more detailed modelling to relate the increased risks of developing pneumoconiotic abnormalities to environmental conditions in specific tasks and locations underground.

Discussion

The men surveyed have shown clear evidence of radiological progression which in its extent and rapidity was atypical of coalworkers in modern mining conditions and of the Scottish coalfield throughout its history. The risks were much higher than would be expected from the overall levels of dust exposure, had the composition of the dust been more typical of coal mining.[14] Most of the progression took place after the main exposure ended, a known feature of silicosis[21] and again atypical of response to coal mine dust. The size and direction of the effects make it implausible that they could be artefacts of selection or response bias, or of imprecisions in the exposure estimates, which in the PFR are much better differentiated than in most other occupational epidemiology.

These findings, and the strong link with the quartz exposure data of the 1970s, suggest that most or all of the progression represents silicosis rather than coalworkers' pneumoconiosis. The unusual nature of the exposures, and of the responses they have induced, suggest that the medical surveillance of the population should be continued if at all possible. Such surveillance might usefully prioritise attempts to examine men who worked in occupations where the quartz concentrations were highest. We note here that all the original target group of 1416 men are included in a separate current study of coalminers' mortality; which will allow, in time, examination of the patterns of mortality in the group.

Figure 2 summarises the trend of risk with increasing exposure to respirable quartz from the regression models fitted. Model A of table 7 was used to predict the risk that the radiograph of a man appearing at follow up would produce a median reading of 2/1 or greater, as a function of the ISP 3–6 respirable quartz exposure. The vertical dashes above the horizontal exposure axis show the positions of the exposures in the data set from which the regression equation was estimated, one dash per subject. The five highest exposures, between 11.3 and 14.4 ghm^{-3}, are omitted.

To convert between exposure and airborne concentration, we note that ISP 3–6 was about 15 years, and a typical working year was reckoned to be 1740 hours, so that to experience an average concentration of 0.5 mg.m^{-3} would produce an exposure of

$0.5 \times 15 \times 1.74 = 13$ ghm^{-3}, implying a very high risk. An average exposure of 0.1 $mg.m^{-3}$ would give an exposure of 2.6 ghm^{-3}, with a risk of about 5%. From table 6, we know that 20% of the men had exposures in excess of 5.7 ghm^{-3}, and therefore risks in excess of about 10%. Note, however, that these are mean concentrations, not occupational exposure limits; and any assessment of the risks associated with particular occupational exposure limits must take into account that mean exposures should remain below the appropriate occupational exposure limit in a well controlled work environment.

Although the predictions of fig 2 may be useful as a guide, they are only as good as the model that produces them, which in this case was a simple logistic regression based on estimates of quartz exposure over a period when conditions changed rapidly in the affected colliery. Indeed, the results summarised in table 8 suggest that this model is an oversimplification: quartz exposures in ISP 3 were estimated by the same methods as in ISPs 4 and 5, yet the coefficient for ISP 3 in model L is about two thirds that for ISPs 4 and 5. This difference is in the wrong direction to be explained by quartz persisting in the lung after deposition. Possible explanations include thresholds for the effect of quartz, differential effects of exposures at different concentrations (including perhaps short periods of very high exposure), and mixtures of different types or sources of quartz, with different risks. Further modelling of the relations between risks and elements of exposure is possible with the highly detailed exposure data available, and such modelling could include alternative dosimetric formulations of exposure, to attempt to discriminate between these possibilities. Understanding of these phenomena would assist prediction of risks from lower exposures, and inform the debate on control limits for quartz.

Almost all exposure to quartz is in the form of mixtures with other minerals. Even when the source material is apparently pure quartz, the percentage of quartz in the respirable dust can be 30% and lower.[22] This implies that the results of this study, and the risk estimates produced, may be relevant to risks from quartz for industry in general; and that, with satisfactory modelling of the shape of the exposure-reponse relation and suitable allowance for the relation between mean concentrations and occupational exposure limits, they may inform the debate on control limits for other industries with exposure to quartz in mixed dust.

We are grateful for financial support from British Coal. The local knowledge of past and present British Coal employees, and particularly of the late Mr P Hogg, were invaluable in identifying and tracing ex-workers. The data from the follow up surveys were collected by a team supervised by radiographers Mrs B Hamilton and Ms J Jeffryes and including Mr J Allan, Mr P Johnston, Mr T Campbelton, and Mr W Scott. The panel for the epidemiological reading exercise was Dr A Rickards, Professor A Seaton, and Dr J Bennett. Data were entered into the computer by Ms Margaret Burnett and Ms Margaret Parker.

1 Muir DCF, Shannon HS, Julian JA, *et al*. Silica exposure and silicosis among Ontario hardrock miners: I Methodology. *Am J Ind Med* 1989;**16**:5–11.
2 Verma DK, Sebestyen A, Julian JA, *et al*. Silica exposure and silicosis among Ontario hardrock miners: II Exposure estimates. *Am J Ind Med* 1989;**16**:13–28.
3 Muir DCF, Julian JA, Shannon HS, *et al*. Silica exposure and silicosis among Ontario hardrock miners: III Analysis and risk estimates. *Am J Ind Med* 1989;**16**:29–43.
4 Hnizdo E, Sluis-Cremer GK. Risk of silicosis in a cohort of white South African gold miners. *Am J Ind Med* 1993;**24**:447–57.
5 Graham WGB, Ashikaga T, Hemenway D, *et al*. Radiographic abnormalities in Vermont granite workers exposed to low levels of granite dust. *Chest* 1991;**100**:1507–14.
6 Ng TP, Chan SL. Quantitative relation between silica exposure and development of small opacities in granite workers. *Ann Occup Hyg* 1994;**38**:857–63.
7 Love RG, Waclawski ER, Maclaren WM, *et al*. *Cross-sectional study of risks of respiratory disease in relation to exposures of airborne quartz in the heavy clay industry*. Edinburgh: Institute of Occupational Medicine, 1994. (IOM Report TM/94/07.)
8 Pilkington A, Maclaren W, Searl A, *et al*. *Scientific opinion on the health effects of airborne crystalline silica*. Edinburgh: Institute of Occupational Medicine, 1995. (IOM Report TM/95/08.)
9 Seaton A, Dick JA, Dodgson J, *et al*. Quartz and pneumoconiosis in coal miners. *Lancet* 1981;ii:1272–5, ([letter] 1982; **i**:45–6.)
10 Miller BG, Kinnear AG. *Pneumoconiosis in coalminers and exposure to dust of variable quartz content*. Edinburgh: Institute of Occupational Medicine. (IOM Report TM/88/17.)
11 Miller BG, Jacobsen M. Dust exposure, pneumoconiosis and coalminers' mortality. *Br J Ind Med* 1985;**42**:723–33.
12 International Labour Organisation. *Guidelines for the use of ILO international classification of radiographs of pneumoconiosis*. Geneva: ILO, 1980. (ILO Occupational Safety and Health Series No 22 (rev 80).)
13 Dodgson J, Whittaker W. The determination of quartz in respirable dust samples by infrared spectrophotometry, II. *Ann Occup Hyg* 1973;**16**:389–95.
14 Hurley JF, Copland L, Dodgson J, *et al*. *Simple pneumoconiosis and exposure to respirable dust: relationships from twenty-five years' research at ten British coalmines*. Edinburgh: Institute of Occupational Medicine, 1979. (IOM Report TM/79/13.)
15 Hurley JF, Burns J, Copland L, *et al*. Coalworkers' simple pneumoconiosis and exposure to dust at 10 British coalmines. *Br J Ind Med* 1982;**39**:120–7.
16 Robinson BN, Anderson GD, Cohen E, *et al*. *SIR scientific information retrieval. Users' manual version 2*. Evanston (Ill): SIR, 1980.
17 Dixon WH, Brown MB, Engelman L, *et al*, eds. *BMDP statistical software manual*. Berkeley, CA: University of California Press, 1988.
18 Genstat 5 Committee. *Genstat 5 reference manual*. Oxford: Clarendon Press, 1987.
19 Collett D. *Modelling binary data*. London: Chapman and Hall, 1991.
20 Miller BG, Hagen S, Love RG, *et al*. *A follow-up study of coalminers exposed to unusual concentrations of quartz*. Edinburgh: Institute of Occupational Medicine, 1995. (IOM Report TM/95/03.)
21 Westerholm P. Observations on a case register. *Scand J Work Environ Health* 1980;**6** (suppl 2):1–86.
22 Davies LST, Robertson A, Agius RM, *et al*. The use of compliance monitoring for assessing quarry workers' exposures to respirable dust and quartz. In: Dodgson J, McCallum RI, eds. *Inhaled particles VII*. Oxford: Pergamon Press, 1994:559–70.