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Chronic obstructive pulmonary disease in Welsh slate miners

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Background	Exposure to respirable crystalline silica (RCS) causes emphysema, airflow limitation and chronic obstructive pulmonary disease (COPD). Slate miners are exposed to slate dust containing RCS but their COPD risk has not previously been studied.
Aims	To study the cumulative effect of mining on lung function and risk of COPD in a cohort of Welsh slate miners and whether these were independent of smoking and pneumoconiosis.
Methods	The study was based on a secondary analysis of Medical Research Council (MRC) survey data. COPD was defined as forced expiratory volume in 1 s/forced vital capacity (FEV_1/FVC) ratio <0.7. We created multivariable models to assess the association between mining and lung function after adjusting for age and smoking status. We used linear regression models for FEV_1 and FVC and logistic regression for COPD.
Results	In the original MRC study, 1255 men participated (726 slate miners, 529 unexposed non-miners). COPD was significantly more common in miners (n = 213, 33%) than non-miners (n = 120, 26%), $P < 0.05$. There was no statistically significant difference in risk of COPD between miners and non-miners when analysis was limited to non-smokers or those without radiographic evidence of pneumoconiosis. After adjustment for smoking, slate mining was associated with a reduction in %predicted FEV_1 [β coefficient = −3.97, 95% confidence interval (CI) −6.65, −1.29] and FVC (β coefficient = −2.32, 95% CI −4.31, −0.33) and increased risk of COPD (odds ratio: 1.38, 95% CI 1.06, 1.81).
Conclusions	Slate mining may reduce lung function and increase the incidence of COPD independently of smoking and pneumoconiosis.
Key words	Mineral dust; miners; occupational lung diseases.

Introduction

Slate has been mined in North Wales for centuries and mines were important employers in the region, employing nearly 18 000 men at the industry's peak in the late 19th century. Slate production has decreased over the years and many of the larger mines have closed. However, smaller-scale mining producing tiles and aggregate continues. Some of the closed mines have been transformed into visitor attractions and in recognition of the industry's importance in Welsh history and culture. The Wales Millennium Centre in Cardiff is clad in slate tiles of different colours from mines in North Wales.

Slate contains crystalline silica, mainly in the form of quartz, which can produce respirable dust when sawed or split; inhaled silica is fibrogenic and can cause silicosis and precipitate tuberculosis. A number of studies have been conducted in North Wales assessing the health of men working in the slate industry [1–3] and have variously observed high rates of both pneumoconiosis and tuberculosis. In 1975, the Medical Research Council (MRC) Pneumoconiosis Unit conducted a cross-sectional survey of slate miners and non-miners in the region [4] and reported an increased risk of pneumoconiosis in exposed miners and a high prevalence of radiological lesions suggestive of healed tuberculosis. A mortality analysis of this cohort of miners to 1998 [5] reported

a clear excess death rate, chiefly from pneumoconiosis but also from other non-malignant respiratory disease, in slate workers compared to controls after adjustment for age and smoking habit.

There is accumulating evidence that occupational respirable crystalline silica (RCS) exposure can also cause chronic obstructive pulmonary disease (COPD). Studies of RCS and COPD have been limited to gold and other hard rock miners, coal miners, granite crushers, concrete workers [6] and uranium miners [7]. To our knowledge, no published studies have investigated COPD in slate miners. This analysis uses lung function data from the 1975 MRC survey to assess whether slate miners in North Wales have an increased risk of COPD.

Methods

The 1975 cross-sectional survey (MRC Pneumoconiosis Unit) took place in four slate mining and quarrying areas in North Wales: Blaenau Ffestiniog, Penygroes, Bethesda and Llanberis [4].

Random samples of ~400 men were identified from the electoral rolls of each of the four areas and selected individuals were visited to assess their occupational history in the slate mining industry (n = 1731). Those under the age of 30 who had never worked in slate mining were excluded (n = 311) as were those who had lived outside the area for >20 years and had not worked in slate mining (n = 150). The remaining men (n = 1270) and those currently employed in slate mining (n = 392) were invited to attend a clinic where the following data were collected: age, height, weight, smoking status, respiratory symptoms (using a bilingual translation of the MRC respiratory symptoms questionnaire), details of attendance at pneumoconiosis medical panels and chest clinics, exposure history to mouldy hay and domestic birds, occupational history, pneumoconiosis category based on posterior and lateral radiographs and lung function [forced expiratory volume in 1 s (FEV_1) and forced vital capacity (FVC)] measured without the use of a bronchodilator. Individuals with mixed dust exposure in their occupational history were excluded (n = 307).

Chest radiographs were assessed by three experienced readers using the ILO-U/C (1976) classification. Methods to resolve disagreements in the interpretation of radiographs are described elsewhere [4]. Based on the assessments of the readers, a score from 0 to 3 for 'simple pneumoconiosis' was allocated using the method devised by Oldham [8].

We did not consider our further analysis of survey data, described below, to pose any significant ethical issues and did not seek additional ethical approval.

The main outcome variables we used were FEV_1, FVC and COPD (yes/no) defined as $FEV_1/FVC < 0.7$, measured at the time of the survey.

We report continuous variables as means (SD) or medians (interquartile range) based on their distribution. We used two-sample t-tests (assuming unequal variance) to compare normally distributed continuous variables between groups and, where variables are skewed, the Mann–Whitney test. We present count data as frequencies and proportions and analyse them using the chi-square test for independence. We used linear regression models adjusting for age and height to generate sample-specific per cent predicted values for FEV_1 and FVC.

We used multivariable models to assess the association between mining and lung function after adjusting variably for age and smoking status. We used binary terms (ever versus never) for smoking and mining. To assess whether lung function measures were associated with duration of exposure, independently of age, we created a series of adjusted models stratified by age (tercile) and included in the models duration of exposure, age (continuous) and smoking status. To minimize the possibility that the reduced lung function in miners was due to pneumoconiosis, we excluded from this group any miner with radiological evidence of pneumoconiosis (n = 72). We used linear regression models for FEV_1 and FVC and logistic regression for COPD. We present results from these models as β coefficients [95% confidence interval (CI)] and odds ratios (95% CI), respectively.

We performed all analyses using STATA v13 (StataCorp LP, College Station, TX, USA).

Results

After initial screening, 1255 men agreed to participate in the survey: 726 (ever-) slate workers and 529 unexposed men. The two groups were generally similar in age, height, weight and smoking history whereby most were either current or ex-smokers (Table 1).

By the time of the 1975 survey, the duration of slate mining exposure ranged greatly from 1 to 72 years and half of the miners were exposed for 15 years or more. Workers with shorter durations of exposure tended to be younger reflecting both the duration of their working lives and the downscaling of the mining industry over the years (1–8 years of exposure – median age = 32.5 years; 9–24 years of exposure – median age = 47.7 years; 25+ years of exposure – median age = 63.1 years).

Valid FEV_1 and FVC data were available on 1117 and 1114 men, respectively, in equal proportions for miners and non-miners. Both measures were lower in slate miners as was the FEV_1/FVC ratio (Table 2). When evaluated as 'per cent predicted' values, the same patterns emerged. Almost a third of miners had COPD—defined as $FEV_1/FVC < 0.7$—compared with a quarter of non-miners. We also explored whether each individual's FEV_1 was 1 L or more below their predicted value, the criterion used in the UK Industrial Injuries Disablement scheme for the

Table 1. Demographic characteristics of participants and exposure history of slate miners

	All (n = 1255)	Slate miners (n = 726)	Non-miners (n = 529)	P value
Age at survey, mean (SD)	48.9 (16.1)	49.1 (17.1)	48.5 (14.8)	NS
Height (cm), mean (SD)	169.6 (6.7)	169.1 (6.7)	170.3 (6.8)	*
Weight (kg), mean (SD)	72.5 (11.9)	72.2 (11.4)	73.1 (12.5)	NS
Smoking history, n (%)				
Never	197 (16)	106 (15)	91 (17)	NS
Ex-smoker	293 (24)	172 (24)	121 (23)	
Current (including pipe)	755 (60)	441 (61)	314 (60)	
Duration of slate mining (years), median (min, max)		15 (1, 72)	–	
Terciles, n (%)				
1–8 years		263 (36)		
9–24 years		221 (31)		
25+ years		240 (33)		

NS, non-significant.
*P < 0.5.

Table 2. Observed and predicted lung function measurements in slate miners and non-miners

	All (n = 1255)	Slate miners (n = 726)	Non-miners (n = 529)	P value
FEV_1 (L), mean (SD)	3.09 (1.00)	3.01 (1.03)	3.20 (0.93)	***
FEV_1 %predicted, mean (SD)	100 (2.6)	98 (2.7)	103 (2.2)	**
FVC (L), mean (SD)	4.16 (1.04)	4.08 (1.05)	4.28 (1.01)	***
FVC %predicted, mean (SD)	100 (16.6)	99 (16.8)	101 (16.3)	*
FEV_1/FVC, median (IQR)	0.75 (0.68, 0.81)	0.75 (0.67, 0.81)	0.76 (0.70, 0.82)	*
COPD				
FEV_1/FVC ≥ 0.7, n (%)	781 (70)	437 (67)	344 (74)	*
FEV_1/FVC < 0.7, n (%)	333 (30)	213 (3)	120 (26)	
Observed FEV_1 ≥ 1 L below predicted for age and height, n (%)				
No	1039 (94)	604 (93)	435 (94)	NS
Yes	72 (7)	45 (77)	27 (6)	

IQR, interquartile range; NS, non-significant.
*P < 0.5, **P < 0.1, ***P < 0.01.

compensation of underground coal miners on the basis that it represents significant impairment of lung function and is associated with disabling breathlessness [9]. Seven per cent of miners and non-miners combined had such a deficit but the difference between slate miners (7%) and non-miners (6%) was not statistically significant.

The differences between miners who had never smoked and non-miners who had never smoked were not statistically significant (Table 3). Across sub-groups, rates of COPD were lower in never smokers regardless of mining exposure, and both FEV_1 and FVC were higher in never smokers.

The outputs of our multivariable models (Table 4) suggest that slate miners had reduced lung function and an increased risk of COPD regardless of smoking status.

The trend for an increased risk of COPD in those with longer durations of exposure for all age groups was not statistically significant. Results for FEV_1 and FVC per cent predicted were less consistent although there was a clear exposure–response relationship for %predicted FEV_1 among the oldest group.

Slate miners without pneumoconiosis had a statistically significant, though modest, reduction in mean predicted FEV_1 and a higher rate of COPD, which was not statistically significant (Table 5).

Discussion

Our study found that those who worked in slate mining in North Wales had reduced lung function that cannot be wholly explained by smoking or pneumoconiosis. In never smokers, there were significant reductions in lung function in miners but no statistically significant increase in COPD. This may be due in part to the small sample size (n = 197). Those without evidence of pneumoconiosis at the time of survey had small reductions in FEV_1 %predicted but no statistically significant increase in COPD in miners.

Table 3. Observed and predicted lung function measurements in slate miners and non-miners (never versus ever smokers)

Analysis restricted to never smokers	*n* = 197	*n* = 106	*n* = 91	
FEV_1 (L), mean (SD)	3.37 (0.99)	3.23 (1.12)	3.54 (0.78)	*
FEV_1 %predicted, mean (SD)	107 (21.9)	105 (21.5)	110 (22.1)	NS
FVC (L), mean (SD)	4.32 (1.05)	4.18 (1.15)	4.49 (0.88)	*
FVC %predicted, mean (SD)	102 (16.7)	101 (17.3)	104 (15.7)	NS
FEV_1/FVC, median (IQR)	0.80 (0.73, 0.85)	0.77 (0.71, 0.86)	0.81 (0.75, 0.84)	NS
COPD				
FEV_1/FVC ≥ 0.7, *n* (%)	144 (82)	75 (77)	69 (89)	NS
FEV_1/FVC < 0.7, *n* (%)	31 (18)	22 (23)	9 (12)	
Analysis restricted to ever smokers	***n* = 1048**	***n* = 613**	***n* = 435**	
FEV_1 (L), mean (SD)	3.04 (0.99)	2.98 (1.02)	3.14 (0.94)	*
FEV_1 %predicted, mean (SD)	99 (22.5)	97 (22.9)	101 (21.7)	*
FVC (L), mean (SD)	4.14 (1.03)	4.06 (1.03)	4.24 (1.03)	**
FVC %predicted, mean (SD)	100 (16.55)	99 (16.67)	101 (16.31)	NS
FEV_1/FVC, median (IQR)	0.75 (0.68, 0.80)	0.74 (0.67, 0.80)	0.75 (0.69, 0.81)	NS
COPD				
FEV_1/FVC ≥ 0.7, *n* (%)	631 (68)	358 (66)	273 (71)	NS
FEV_1/FVC < 0.7, *n* (%)	298 (32)	188 (34)	110 (29)	

IQR, interquartile range; NS, non-significant.
*$P < 0.5$, **$P < 0.1$.

Table 4. Adjusted regression analyses assessing the associations between mining and smoking on measures of lung function and COPD

	FEV_1 %predicted, β (95% CI)	FVC %predicted, β (95% CI)	COPD (FEV_1/FVC < 0.7), OR (95% CI)
All ages (*n* = 1255)			
Mining	−3.97 (−6.65, −1.29)	−2.32 (−4.31, −0.33)	1.38 (1.06, 1.81)
Smoking (ever)	−8.07 (−11.68, −4.46)	−2.55 (−5.23, 0.13)	2.18 (1.44, 3.29)
Age < 40 years (*n* = 404)			
Age (years)	0.41 (0.16, 0.66)	0.45 (0.26, 0.64)	1.05 (0.99, 1.12)
Mining (referent group: no exposure)			
1–8 years	0.51 (−2.92, 3.95)	−0.13 (−2.70, 2.43)	1.04 (0.45, 2.36)
≥9 years	−2.00 (−6.18, 2.17)	−0.89 (−4.00, 2.23)	1.39 (0.58, 3.33)
Smoking	−3.14 (−6.78, 0.50)	−1.00 (−3.72, 1.72)	1.25 (0.50, 3.15)
Age 40–54 years (*n* = 380)			
Age (years)	−0.30 (−0.80, 0.21)	−0.05 (−0.44, 0.33)	1.09 (1.03, 1.16)
Mining (referent group: no exposure)			
1–8 years	−8.10 (−14.38, −1.83)	−5.47 (−10.27, −0.67)	1.32 (0.66, 2.65)
9–24 years	−2.42 (−7.92, 3.07)	−0.37 (−4.55, 3.80)	1.13 (0.60, 2.11)
≥25 years	−5.77 (−12.18, 0.65)	−3.13 (−8.01, 1.74)	2.05 (1.03, 4.09)
Smoking	−11.18 (−17.75, −4.60)	−3.32 (−8.31, 1.67)	3.17 (1.26, 7.98)
Age 55+ years (*n* = 467)			
Age (years)	0.15 (−0.29, 0.59)	−0.31 (−0.64, 0.02)	1.06 (1.03, 1.10)
Mining (referent group: no exposure)			
1–8 years	2.73 (−9.06, 14.51)	3.67 (−5.01, 12.35)	1.07 (0.46, 2.46)
9–24 years	−6.66 (−15.43, 2.11)	−4.71 (−11.17, 1.75)	1.26 (0.68, 2.34)
≥25 years	−7.65 (−14.47, −0.82)	−2.33 (−7.37, 2.72)	1.55 (0.95, 2.52)
Smoking	−14.38 (−22.64, −6.12)	−6.50 (−12.58, −0.42)	2.45 (1.32, 4.53)

NS, non-significant; OR, odds ratio.

There were a number of strengths to our study. The unexposed group was selected from the same community and showed no meaningful differences in smoking habits or lung function measures. The similarities in smoking rates suggest that the groups are roughly similar socio-economically. The nature of mining in North

Table 5. Analyses omitting miners with evidence of pneumoconiosis

	All (n = 1178)	Slate miners without pneumoconiosis (n = 649)	Non-miners (n = 529)	P value
FEV_1 (L), mean (SD)	3.15 (0.97)	3.11 (1.00)	3.20 (0.93)	NS
FEV_1 %predicted, mean (SD)	101 (21.9)	99 (21.5)	103 (22.2)	*
FVC (L), mean (SD)	4.23 (1.00)	4.19 (0.99)	4.28 (1.01)	NS
FVC %predicted, mean (SD)	101 (15.9)	100 (15.6)	101 (16.3)	NS
FEV_1/FVC, median (IQR)	0.76 (0.69, 0.81)	0.76 (0.70, 0.82)	0.75 (0.68, 0.81)	NS
COPD				
FEV_1/FVC ≥ 0.7, n (%)	751 (71)	407 (69)	344 (74)	NS
FEV_1/FVC < 0.7, n (%)	304 (29)	184 (31)	120 (26)	

IQR, interquartile range; NS, non-significant.
*P < 0.5.

Wales and the initial screening process ensured that those involved in slate mining were unlikely to have been exposed to coal dust. Additionally, lung function measurements were not collected through routine screening but were performed by the same study team at approximately the same time. A number of limitations arise in particular from the cross-sectional design. As individuals in the study had such a wide range in years of exposure, we are covering a long period in slate mining history over which it would be natural to assume that exposures and working practices would have changed greatly. We cannot exclude the possibility that the nature of exposure was different in different mines. We did not have information necessary to examine this. Those surveyed represent a 'survivor' population [10] and it is probable that from the currently employed population, some miners may have left because of respiratory diseases or industrial accidents before the survey. Smoking data, although collected in the same way in both populations, were relatively crude and we did not have data on pack-years.

The increased risk of COPD with increasing duration of exposure was not consistent across all age groups, and not always statistically significant. The data show that such differences are greatest when comparing those unexposed with those having the longest duration of exposure. However, due to the high correlation between age and duration of exposure, disentangling the associations for each is difficult. We note that Campbell *et al.* [5] found that after allowing for the effects of smoking, there were excess deaths from pneumoconiosis. Together with available radiographic data, the majority of which did not show pneumoconiosis, they suggested that there may have been a tendency to ascribe deaths to pneumoconiosis which were in fact due to underlying airways obstruction and a fatal exacerbation.

Respirable slate dust in the North Wales mines contains between 13 and 32% respirable quartz [4]. Recent measurements from two slate processing sites in North Wales (a slate crushing operation and production of roofing slates by sawing and hand-cleaving of blocks) reported personal RCS exposures to be between 0.1 and 0.3 mg/m^3 for the majority of measurements [11]. Historic RCS measurements for slate miners in the MRC cohort are unavailable but are likely to have exceeded this. Interestingly, an excess of deaths from emphysema (standardized mortality ratio: 1.59, P < 0.05) was observed in the pre-1940 high exposure group (working in an environment with 0.2 mg/m^3 of RCS) of the Vermont Granite Mortality Study [12]. The Vermont State Health Department established a threshold limit of 10 mppcf (~0.1 mg/m^3 of RCS) in 1938, which was achieved as an average exposure subsequent to 1940. After adjustment for smoking, no significant association between FEV_1 decline and RCS exposure was observed for Vermont granite workers who started work after 1940 [13]. Modest FEV_1 loss with obstructive pattern lung function that cannot be explained by pneumoconiosis or smoking has been observed in several studies of workers with RCS exposure [6] but clear exposure threshold limit values for COPD have not yet been established. Airflow limitation is thought to be mediated by emphysema, which post-mortem studies have shown bears an exposure–response relationship with silica exposure [14], possibly arising from silica-induced inflammation with inactivation of alpha-1 antitrypsin [15]. Epidemiological studies of RCS and COPD include community and occupational cross-sectional studies and cohort studies where radiological imaging has not shown signs of silicosis. For example, in Western Norway, an area that consists mainly of mountains that are rich in quartz minerals, a cross-sectional community survey found that 13% (n = 3445) of 26 106 participants had self-reported occupational exposure to quartz. Each year of quartz exposure was associated with a 4.3 ml (95% CI 1.1–7.5 ml; P < 0.01) reduction in FEV_1 after adjusting for age, atopy, asthma, wheezing, marital status and other occupational exposures; the comparable reduction attributable to smoking was 6.9 ml (95% CI 4.7–9.1 ml; P < 0.01) from smoking 20 cigarettes/day for 1 year [16]. Similarly, in a cohort study of 45 granite crushers from Uppsala, Sweden, in which the mean cumulative amount of inhaled silica was 7 mg over 22 years, workers had, over a 12 year interval,

a 5% greater decrease in FEV_1 compared with referents matched, for age and smoking [17]. A cross-sectional study of 144 concrete workers from the Netherlands found no significant change in FEV_1 and only a small statistically significant change in FEV_1/FVC associated with an average exposure of 0.566 silica-years (mg/m^3/year) [18]. A recent study of 1421 study subjects from the Wismut cohort of former uranium miners found that cumulative exposure of 1 mg/m^3 year respirable quartz leads to an average reduction in FEV_1/FVC of 3% ($P < 0.001$) [7].

It is well established that while cigarette smoking is the most important single causal factor for developing COPD, it is not the sole causal factor and occupational exposures are also causal [19]. We present the novel finding of airflow limitation that cannot be attributed to pneumoconiosis or smoking among workers exposed to RCS in slate mines—consistent with an accumulating body of evidence for an increased risk of COPD due to RCS. This is important for occupational health providers in the few remaining slate mines in North Wales and likely to become an emerging issue internationally in countries with significant slate mining operations such as Spain, Brazil, the USA, and China. In view of the important interaction of smoking and RCS exposure in miners [14], the promotion of non-smoking by occupational health services is likely to be an important preventive strategy. Prospective research into workplace RCS exposure and COPD in these populations would be of value.

Key points

- Slate miners are exposed to slate dust containing respirable crystalline silica but their risk of chronic obstructive pulmonary disease has not previously been studied.
- Our results show an increased risk of chronic obstructive pulmonary disease in slate miners, which is independent of smoking status and pneumoconiosis.
- Occupational health providers to slate mines should seek to minimize slate dust exposure and consider workplace surveillance measures for chronic obstructive pulmonary disease.

Conflicts of interest

None declared.

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