Coal dust exposures in the longwall mines of New South Wales, Australia: a respiratory risk assessment

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This paper presents an analysis of personal respirable coal dust measurements recorded by the Joint Coal Board in the underground longwall mines of New South Wales from 1985 to 1999. A description of the longwall mining process is given. In the study, 11 829 measurements from 33 mines were analysed and the results given for each occupation, for seven occupational groups, for individual de-identified mines and for each year of study. The mean respirable coal dust concentration for all jobs was 1.51 mg/m³ (SD 1.08 mg/m³). Only 6.9% of the measurements exceeded the Australian exposure standard of 3 mg/m³. Published exposure–response relationships were used to predict the prevalence of progressive massive fibrosis and the mean loss of FEV₁, after a working lifetime (40 years) of exposure to the mean observed concentration of 1.5 mg/m³. Prevalences of 1.3 and 2.9% were predicted, based on data from the UK and the USA, respectively. The mean loss of FEV₁ was estimated to be 73.7 ml.

Key words: Coal; chronic obstructive pulmonary disease; longwall; mining; pneumoconiosis; progressive massive fibrosis; underground.

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Introduction

The longwall mining process

The two most important methods of underground mechanized coal mining are bord and pillar, and longwall. Over the last 10 years, longwall mining has become the predominant method in use in New South Wales (Figure 1). In bord and pillar mining, continuous mining machines extract coal in a grid shaped pattern, leaving unmined pillars of coal supporting the roof. In longwall mining, a panel of coal is extracted by a shearer which slices coal from the face as it passes repetitively along it, retreating into the panel with each slice. Panels are typically 200 m wide at the face and 2000 m long, with a 3 m seam height, and are mined at a depth of ~250 m [1]. The roof is allowed to collapse behind the retreating shearer, leaving a collapsed section called the goaf. In Australia, shearers extract seam thicknesses from 1.8 to 5.5 m [2]. Some seams are up to 24 m thick and the remaining unextracted coal is sterilized (wasted) in the goaf [2]. Figure 2 is a three-dimensional diagram of a typical longwall operation.

The mine plan in Figure 3 is typical of an Australian longwall mine. It shows how the seam is divided into several parallel longwall panels. Longwall faces in Australia predominantly use the retreating method of extraction, as distinct from the advancing method [3]. The longwall panel is formed by a number of development headings, which are used for ventilation purposes during extraction [4]. Two headings in the maingate development and five to seven ‘mains’ (intake and return roadways) are commonly used in Australian longwall mines [2]. The maingate headings are driven from the mains to the end of the panel and connected to the previous goafs’ maingate, which then becomes the tailgate of the new panel. A rectangular panel of coal is thus defined. As the coal is extracted by the shearer, the
roof supports (also termed chocks or shields) advance sequentially and the roof in the mined-out area falls, forming the goaf. In the maingate cut-throughs, between pillars, temporary wall structures called ‘stoppings’ are erected during development to facilitate ventilation. In the tailgate cut-throughs, more permanent wall structures called ‘seals’ impede the mixing of ventilation and goaf atmospheres (Figure 2). Mined coal is transferred to the surface through the panel belt conveyor and main conveyor that runs in the intake heading.

Commonly, the ventilation circuit is U shaped, with intake air flowing along the maingate roadways and air from the face returning along the tailgate roadway as shown in Figures 2 and 3. Alternative ventilation circuits are sometimes used, especially in gassy mines.

Longwall components

Longwall systems consist of the following components, illustrated in Figure 2:

- Shearer: the remote-controlled shearer cuts the coal, which falls onto the armoured face conveyor. Shearer-initiated shield advance (SISA) provides automatic roof support advance.
- Armoured face conveyor (AFC): the AFC delivers coal from the longwall face to the transfer point.
- Hydraulic roof supports: roof supports prevent roof fall at the face and provide a walkway for people working at the face.
- Maingate transfer: coal is transferred from the AFC to the beam stage loader (BSL) at the maingate transfer point.
- Beam stage loader: coal is transferred from the maingate transfer point onto the BSL and delivered through the crusher onto the belt conveyor.

Figure 1. New South Wales coal production, 1970–2000 (courtesy of the New South Wales Department of Minerals Resources).

Figure 2. A typical retreating longwall operation with conventional U shaped ventilation (courtesy of Anglo Coal Australia Pty Ltd).
- Crusher: coal is crushed within the BSL crusher. This facilitates conveying.
- Mobile belt tailpiece: the mobile belt tailpiece enables the constant flow of coal from the longwall face without stopping of the belt.

Figure 4 is a photograph of a longwall face. It shows a shearer operator standing under the roof supports, operating the shearer, with coal falling onto the AFC. More details on longwall mining can be obtained from the University of Wollongong longwall mining website [3].
Longwall changeout

When one panel has been completed, all the longwall equipment is dismantled and transferred to the new face for installation. This process is called 'longwall changeout' and consists of two phases: recovery and installation. Prior to installation, major maintenance of the longwall equipment is carried out. Additional temporary roof support is necessary to ensure satisfactory ventilation and protection from roof fall, for the duration of the recovery. Production is lost during changeout.

Sources of dust

Longwall mining generates up to four times as much dust as a continuous miner [4]. Sources of dust on a longwall face include [4,5] the following:

- The shearer: cutting the coal is a major source of dust.
- Roof support movement: dust that has settled on the chocks and crushed roof material lying between the roof support canopy and the roof is dispersed into the air as the supports are advanced.
- Spalling of coal: coal spalling (falling as a large lump rather than being cut by the shearer) from the face creates dust.
- Transfer points and crusher: dust is created at the maingate transfer point when coal changes direction forcefully from the AFC to the BSL, and during passage through the crusher.
- Boot end: dust is created as coal leaves the BSL at the boot end.
- Goaf falls: when the roof falls to form goaf, some of the dust escapes into the face area.
- Coal spillage: coal spillage at the transfer point and coal movement on the conveyor create dust.
- Roadway dust: intake air is contaminated by dust, which has accumulated on the roadway floors, when it is disturbed by traffic.

Control of dust

Longwall dust control measures include the following [4–6]:

- Shearer drum sprays: water is sprayed through nozzles mounted on the shearer drum near or in the bit blocks.
- Shearer clearer system: a shearer-mounted spray system that is orientated so that ventilation air striking the shearer is directed towards the face and away from the walkway.
- Water infusion of longwall panels: water is injected under pressure into the coal seam ahead of the face [7]. Gas drainage holes are sometimes used.
- Minimizing air leakage from the goaf onto the face, by using brattice cloth (a strong fire-resistant fabric).
- Increased face airflow: a high airflow dilutes the dust faster. However, increased air velocity may cause more dust to become airborne [7].

- Homotropol ventilation: when the coal conveyors and airflow move in the same direction, dust created by the transfer points and crusher is not transferred to the face.
- Modified coal-cutting techniques: uni-directional cutting reduces dust concentrations compared to bi-directional cutting. In uni-directional cutting, the shearer must make two passes of the face to extract one shearer drum width of the full seam thickness. In bi-directional cutting, a drum width is extracted with one pass of the shearer.
- Using sharp shearer drum picks: blunt picks create more dust.
- Reductions in the shearer cutting speed.
- Enclosing the stage loader and belt transfer points.
- Installation of water sprays inside these enclosures.
- Exhaust ventilation of the enclosures to the return airway, where possible.
- Exhaust ventilation and water sprays at the crusher.
- Regular maintenance of dust suppression controls; for example, ensuring the nozzles are not blocked and that the picks are not blunt.
- Hosing down the chocks to remove surface dust.
- Applying water to the roadways.

Longwall mining in New South Wales

Most coal mining in Australia occurs in the states of New South Wales and Queensland. Longwall mining was first introduced to New South Wales in 1962 [8]. Currently, there are 34 longwall mines in Australia and 23 of them are in New South Wales [9]. Figure 1 illustrates the amount of coal produced by longwall, bord and pillar, and open-cut methods in New South Wales for the period 1970/1971–1999/2000. Longwall production has increased substantially from 2.2 Mt (4% of total coal production) in 1980–1981, to 24.5 Mt (25% of total production) in 1990–1991, to 43.5 Mt (33% of total production) in 1999–2000.

In 1996/1997, New South Wales longwall production accounted for ~4.8% of world coal extracted by longwalls [10,11].

The major coal deposits of New South Wales range from bituminous coking and thermal coals to sub-bituminous thermal coals [11]. The coal is classified as medium to high rank.

The role of the Joint Coal Board in New South Wales

The Joint Coal Board is a statutory body in New South Wales. It provides the New South Wales coal mining industry with an occupational health service that provides medical assessments, injury management, workplace
environmental monitoring and health educational material [12]. The Joint Coal Board also operates the workers compensation insurance scheme for the New South Wales coal mining industry.

In 1954, the Joint Coal Board established the Standing Committee on Dust Research and Control. This tripartite committee (including coal company representatives, union check inspectors, government inspectors, consultants, occupational physicians and Joint Coal Board specialists) undertakes the following main roles (personal communication, Joint Coal Board):

- Monitoring of respirable dust results.
- Evaluation of dust risks.
- Encouragement to improve dust control methods.
- Dissemination of information and the education of mine personnel.

The committee meets bimonthly and conducts the majority of its meetings at mine sites.

The Joint Coal Board has undertaken personal gravimetric samples of respirable coal dust in coal mines since 1984 [13]. Before 1984, the particle counting method was used [13]. Samples are collected by Joint Coal Board Officers at least every 6 months at longwall faces, during a production shift. Samples are taken from the breathing zone of at least five operators, including at least one shearer operator, two roof support operators, a deputy and one other person selected by the mine manager [13]. SIMPDES cyclones are used, which sample the respirable fraction of dust according to the UK Medical Research Council curve. The samples are analysed at the Joint Coal Board laboratory [13].

The Joint Coal Board undertakes chest X-rays on average every 3 years for current underground miners and every 5 years for current surface miners (personal communication, Joint Coal Board). The entire workforce is sampled and all current miners are expected to participate in this health surveillance. The prevalence of coal worker’s pneumoconiosis in miners has declined substantially in recent decades, from 16.0% in 1948 to consistently <0.5% during the period 1990–2000 [12,14,15] (Joint Coal Board, personal communication). All of the current cases are below International Labour Office (ILO) profusion category 2 [12].

In this paper, we present an analysis of the Joint Coal Board’s longwall exposure data, for the years 1985–1999. The aims of the analysis were:

1. To determine recent compliance with the national exposure standard.
2. To estimate the future prevalence of coal worker’s pneumoconiosis and progressive massive fibrosis and the mean loss of FEV1 due to chronic obstructive pulmonary disease, in lifetime miners (40 years of exposure), using published exposure–response relationships.

### Methods

We analysed the Joint Coal Board database of personal respirable coal dust concentrations for the period 1985–1999. There were several identifiers in the database, including mine code, date and job. We constructed seven occupational groups from 28 of the 41 jobs listed in Table 1, which we thought were likely to stratify the longwall operation by exposure. The occupational groups and their constituent job identifiers are presented in Table 2. A brief description of each constituent job is also given in Table 2.

Attfield and Seixas [16] have published predictions of the prevalence of coal worker’s pneumoconiosis and progressive massive fibrosis after 40 years of exposure to various concentrations of respirable coal dust. Their predictions were based on data from the National Study of Coal Worker’s Pneumoconiosis in the USA and data from the National Coal Board’s Pneumoconiosis Field Research in the UK. Their predictions based on the data from the UK drew on previous works by Hurley and Maclaren [17], and by Attfield [18]. A graph of the exposure–response relationships they derived from the UK and US data for high rank coal is shown in Figure 5. We linearly interpolated the UK prevalences at a concentration of 1.5 mg/m3 from the prevalences given for concentrations of 1.0 and 2.0 mg/m3. We used this graph to make predictions of the prevalence of pneumoconiosis and progressive massive fibrosis after 40 years of exposure to coal dust in the longwalls of New South Wales, using the average measured respirable coal dust concentration.

Soutar and Hurley [19] have estimated the average loss of FEV1, attributable to cumulative coal dust exposure, to be 0.76 ml per ghm–3. In a review of coal mining and chronic obstructive pulmonary disease, Coggon and Newman Taylor concluded that this figure was a reasonable best estimate [20]. If one working year is assumed to be 1600 h, then 0.76 ml per ghm–3 is equivalent to 1.22 ml per mg/m3–year. We used this figure to predict the average loss of FEV1 after 40 years of exposure to coal dust in the longwalls of New South Wales, using the average measured respirable coal dust concentration.

### Statistical analysis

The number, mean and standard deviation of respirable coal dust exposures were calculated for each occupation. The number, mean, 95% confidence interval for the mean, standard deviation, and minimum and maximum values were determined for the respirable coal dust exposures of each of the occupational groups. A box-and-whisker plot of coal dust exposure for each of the seven occupational groups was made. The significance of differences in mean coal dust concentrations between the
seven occupational groups was determined using the Kruskal–Wallis test. Six comparisons between occupational groups were then made, two groups at a time, using the Mann–Whitney U-test. To prevent error inflation due to multiple comparisons, a downward adjustment of the level from 0.05 to 0.008 was made. A box-and-whisker plot was made of coal dust exposure for each of the mines. Another box-and-whisker plot was made of coal dust exposure for each year of the study period. The box-and-whisker plots do not contain outlier or extreme values because of the large coal dust exposure scale that would be needed. SPSS 10.1 for Windows was used for all statistical analyses, following importation of the data from Microsoft Excel spreadsheets.

Results

In total, 11,829 valid measurements from 33 mines were analysed. The seven occupational groups we derived from 28 of the 41 jobs comprise 11,790 (99.7%) of the measurements.

The respirable coal dust exposures (number, mean, standard deviation) for each of the 41 occupations are listed in Table 1. The respirable coal dust exposures (number, mean, 95% confidence interval for the mean, standard deviation, minimum, maximum) for each occupational group are listed in Table 3 and the corresponding box-and-whisker plots are presented in Figure 6. Table 3 also lists the percentages of measurements for each occupational group that exceed 1.0, 1.5, 2.0 and 3.0 mg/m³.
There was insufficient data to characterize exposures during longwall installation and recovery.

Table 4 lists the total number of measurements taken at each mine and the number and percentage of measurements for each mine that exceed 3 mg/m$^3$. Figure 7 presents a box-and-whisker plot of respirable coal dust exposure for each of the 33 mines. The box-and-whisker plot represents the exposures for all occupations over the period 1985–1999. During this period, some of the mines opened, some closed and some changed ownership.

Figure 8 presents a box-and-whisker plot of respirable coal dust exposure for each year from 1985 to 1999. The box-and-whisker plot represents the exposures for all mines and all occupations.

The mean respirable coal dust concentration for all longwall jobs was 1.51 mg/m$^3$. Predictions of the prevalence of coal worker’s pneumoconiosis and progressive massive fibrosis after 40 years of exposure to 1.5 mg/m$^3$ are given in Table 5. These are based on the predictions derived from the UK and US databases by Attfield and Seixas [16], as described in the Methods section.

The predicted average loss of FEV$_1$ after 40 years of exposure to 1.5 mg/m$^3$ is:

$$1.22 \text{ ml per mg/m}^3\text{-year} \times 1.51 \text{ mg/m}^3 \times 40 \text{ years} = 73.7 \text{ ml}$$

The derivation of this prediction was described in the Methods section.

### Discussion

Most of the 33 longwall mines comply well with the
current Australian exposure standard of 3 mg/m³ [21]. However, 16 mines (48.5%) have >5% of measurements in excess of the 3 mg/m³ exposure standard. It is worth noting that four mines (12.1%) have had <50 measurements taken in total and are therefore probably inadequately characterized.

Inspection of the box-and-whisker plots of Figure 7 shows that to comply successfully with the 3 mg/m³ exposure standard, longwall mines need to operate at a median exposure of <1.5 mg/m³.

Given that most mines comply well with the exposure standard, it seems likely that improved application of existing dust suppression and ventilation technology at the mines with the highest concentrations would enable compliance. A standardized survey of the mines may be of benefit, to determine:
Which of the known technologies are applied well in the mines with low dust concentrations.

What are the barriers to the use of these successful methods in mines that have high dust concentrations.

What known technologies, that could further reduce exposure, are not used and what are the barriers to their introduction.

The box-and-whisker plots of Figure 8 show that the industry has been able to prevent substantial increases in exposure during the period 1985–1999, while production has approximately doubled.

There are significant differences in exposure between the occupational groups. As expected, the shearer operators have the highest mean exposure (1.72 mg/m³). They work closest to the shearer where there is exposure to dust as coal is cut from the face and as it falls onto the AFC. They are also exposed to dust from chock movement, spalling of coal and collapse of the roof in the mined area (formation of goaf) behind the chocks. Chockmen have the next highest mean exposure (1.58 mg/m³). They are exposed to the same sources as the shearer operators, but are usually at a greater distance from the shearer. The face operators consist mostly of people rotating between the jobs of shearer operator and chockman. Their mean exposure (1.57 mg/m³) is similar to that of the chock-
men. The maingate men have a significantly lower mean exposure (1.36 mg/m³). This is probably because they are at a greater distance from the above-mentioned sources of dust, except for when the shearer is at the maingate. They are also usually at the upstream end of the face, in relatively fresh air, when U-type ventilation is in use. Maingate men are also exposed to spalling of coal, which may occur even when the shearer has moved away from the maingate. The deputies have a similar mean exposure (1.29 mg/m³) to the maingate men. They supervise the longwall operation and are on the face for only a portion of their shift. Tradesmen have a significantly lower mean exposure (1.15 mg/m³). This is probably because they are also on the face for only a portion of their shift and because the shearer may not be operating while they are there. The boot end men have the lowest mean exposure (0.93 mg/m³). This is probably because they usually work upstream of the face, in relatively fresh air, when U-type ventilation is in use.

Of the seven occupational groups, the shearer operators, the chockmen, the face operators and the maingate men all have >5% of measurements in excess of the 3 mg/m³ exposure standard. It seems clear that if improvements are to be made, they should be targeted at reducing exposure along the face and at the maingate.

The predictions based on the exposure–response relationships published by Attfield and Seixas [16] indicate that if recent exposures are maintained, there remains a risk of pneumoconiosis and progressive massive fibrosis for those people spending a working lifetime as longwall coal miners. The risk of the most serious form of pneumo-

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**Table 4.** The total number of coal dust measurements for each mine and the no. and percentage of measurements >3 mg/m³

<table>
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**Figure 7.** Box-and-whisker plot of respirable coal dust concentration (mg/m³) for each of the 33 mines.
Pneumoconiosis, progressive massive fibrosis, is 1.3 and 2.9% for lifetime miners, based on data from the UK and the USA, respectively. Miller and Jacobsen [22] reported survival rates for coal miners with and without pneumoconiosis over a 22 year period. From their summary data, it is possible to calculate the attributable risk of death of progressive massive fibrosis. For the pre-retirement age group of 55–64 years, the attributable risks over a 22 year period were ~7.1% for category A, 10.3% for category B and 23.1% for category C progressive massive fibrosis. For younger age groups, the attributable risks are higher because of the lower mortality rates from other causes. If one assumes from the predictions that ~2% of lifetime longwall miners will develop progressive massive fibrosis at retirement, then one might further predict from the attributable risks listed above that ~10% of this group will die from their disease. In other words, ~0.2% or 1 in 500 lifetime longwall miners may die of progressive massive fibrosis in their retirement. Given that most miners will probably work for substantially less than 40 years, the overall risk will be much less than this. By way of comparison, the recent fatal injury rate for the Australian mining industry is such that ~2 in 500 to 6 in 500 workers may die from occupational trauma in a 40 year career [23].

The predicted average loss of FEV$_1$ of 73.7 ml over 40 years of exposure to the mean observed concentration of 1.5 mg/m$^3$ seems tolerable. This equates to only 6% of the average FEV$_1$ of a short elderly Caucasian male (1180 ml for an 80-year-old of 145 cm height) [24]. Even allowing for individual variation and the effects of smoking, it seems unlikely that the loss attributable to coal dust exposure at 1.5 mg/m$^3$ would be of clinical significance.

It is important to note that the current practice of wearing particulate respirators at the coalface will probably reduce the risk of respiratory diseases to below the estimates we have derived.

Predictions of the prevalence of coal worker’s pneumoconiosis after 40 years exposure to the mean observed concentration of 1.5 mg/m$^3$ (Table 5) greatly exceed the observed prevalence of <0.5% ILO 1+, for all coal miners in New South Wales. In addition, the observed prevalence is substantially less than that found in the fourth round of the US National Study of Coal Worker’s Pneumoconiosis (3.9% ILO 1+), undertaken 13–16 years after the introduction of the 2 mg/m$^3$ standard [25]. There are several possible explanations for these differences:

<table>
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<th>Category</th>
<th>Predicted % prevalence (UK)</th>
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Data are based on UK and US predictions by Attfield and Seixas [16].

Figure 8. Box-and-whisker plot of respirable coal dust concentration (mg/m$^3$) for each year, from 1985 to 1999.
• The mean duration of work as a coal miner in New South Wales is likely to be substantially less than 40 years, and may be less than that which prevailed in the USA during the National Study of Coal Worker’s Pneumoconiosis survey.
• The dust sampling period in New South Wales is cribroom (an underground rest area near the face) to cribroom, whereas in the USA it is portal to portal. Measurements under the same dust conditions in the USA are therefore systematically lower because the sampling period includes travel in the relatively clean air of roadways.
• There may be a survivor bias, whereby miners with more severe pneumoconiosis have left the industry and are not therefore included in chest X-ray surveillance.
• Bord and pillar mining and surface mining may give rise to lower exposures, thereby diluting the risk.
• Exposure may have increased substantially within a period less than the latent period for coal worker’s pneumoconiosis. However, inspection of Figure 8 suggests this is unlikely, as there has been no substantial increase in exposure over the period 1985–1999.
• Secondary prevention may be more consistently applied and at a lower category of pneumoconiosis. However, the predictions by Attfield and Seixas [16] based on the US data assumed removal of workers of category ILO 1+ to exposures <1 mg/m³. It is unlikely that secondary prevention in New South Wales is more conservative than this.
• The rank of coal may be lower than that of the high rank predictions of Attfield and Seixas [16]. Higher rates of pneumoconiosis are associated with exposure to higher ranks of coal [26–29].
• The crystalline silica content of coal in New South Wales may be lower.
• The exposure–response relationship in New South Wales may be different to that in the USA and the UK. Before being able to comment further on this, a comprehensive study of the respiratory health of miners and ex-miners would be required.
• Coal miners in New South Wales may have used respiratory protection more frequently during the study period 1985–1999 than did miners in the USA and the UK during the earlier study periods, which resulted in the exposure–response predictions published by Attfield and Seixas [16].
• The prevalence of smoking may have been lower in New South Wales during the study period 1985–1999 than in the USA and the UK during the earlier study periods. Smoking can cause minor chest X-ray opacities, although these tend to be irregular opacities, rather than the predominantly rounded opacities of coal worker’s pneumoconiosis [29].

Our analysis has some limitations. We have not included estimates of variability in the predictions of prevalence and loss of FEV₁ after 40 years exposure. This is partly an intentional simplicity, but also there are limited variability data in the published exposure–response relationships. We have not attempted to estimate the future incidence of coal worker’s pneumoconiosis in New South Wales. This would require data on numbers of workers, their age and work duration. Instead, we have used existing exposure–response relationships to predict the prevalence of coal worker’s pneumoconiosis in lifetime miners (40 years exposure) as a means of risk assessment. Finally, two components of the longwall process have not been studied:

1. Longwall changeout (installation and recovery) could not be characterized because of a lack of data. We suggest that more data should be collected during this part of the process in future, especially given that ventilation is likely to be poor.
2. Longwall development was not clearly distinguished from bord and pillar development in the database because these processes are regarded as being essentially the same [15]. We hope to analyse development data in the near future.

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References


