Commentary

To celebrate BOHS’s 50th anniversary this year, we are reproducing in our on-line edition ‘classic papers’ from the past, with accompanying commentaries in the print and on-line edition. For this issue, the classic paper does not come from the Annals itself, but from the proceedings of one of the symposia on inhaled particles which BOHS organized about every five years from 1960 onwards. [The series was reviewed by Corbett McDonald (2001), ‘The quintessence of dust’, Ann Occ Hyg 45: 171–3.] The paper representing this series is Jacobsen M, Rae S, Walton WH, Rogan JM, The relationship between pneumoconiosis and dust-exposure in British coal mines. In Walton WH, editor. Inhaled Particles III. Old Woking: Unwin Bros, 1971, pp. 903–19. One of our commentators, Michael Attfield, was a member of the research team that did this work.

Pneumoconiosis, coalmine dust and the PFR

M. D. ATTFIELD1 and E. D. KUEMPEL2

1Division of Respiratory Disease Studies, National Institute for Occupational Safety and Health, Morgantown, WV 26505; 2Education and Information Division, National Institute for Occupational Safety and Health, Cincinnati, OH 45226, USA

Received 19 June 2003; in final form 26 June 2003

The relationship between pneumoconiosis and dust-exposure in British coal mines’ (Jacobsen et al., 1971), together with the papers by Chamberlain et al. (1971) and Dodgson et al. (1971), marked the culmination of research undertaken for, or contributing to, the Interim Standards Study (ISS) of the British National Coal Board’s Pneumoconiosis Field Research (PFR). The ISS was a special investigation undertaken to develop new dust standards for British coal mines (Jacobsen et al., 1970).

In 1952 the National Coal Board established the PFR in response to an invitation from the United Kingdom National Joint Pneumoconiosis Committee to undertake a field research in order to determine how much and what kinds of dust cause pneumoconiosis and to establish what environmental conditions should be maintained if mine workers are not to be disabled by the dust that they breathe during the course of their work’ (Fay and Rae, 1959). A significant impetus for the research came from the fact that ~36000 coalminers had been determined to be disabled by the disease during the preceding two decades (1931–49) by the British Silicosis Medical Board or the Pneumoconiosis Panels of the Ministry of National Insurance (Cochrane et al., 1951). [Meiklejohn (1952) reported a coalminder population in Britain of ~63000 for 1950.]

During the next 15 yr the PFR pursued an intensive program of careful data collection and analysis. From this background the Jacobsen et al. paper emerged. The strength and influence of this paper lie not only in its own scientific merits, but also depend heavily on the preceding efforts upon which it is based: the rigorous design, the data quality control, and the methodological innovations developed or implemented by the PFR team under the leadership of Dr John Rogan. In addition, a heavy debt is owed to the work undertaken on radiographic assessment by the Periodic X-ray (PXR) Scheme of the British National Coal Board, and the pioneering investigations at the Pneumoconiosis Research Unit of the Medical Research Council.

PNEUMOCONIOSIS FIELD RESEARCH PROGRAM

The PFR began as a study of coalworkers’ pneumoconiosis (CWP), with radiological surveys at 25 collieries. The collieries were selected from the population of all operating underground mines in Britain to conform to a Latin square experimental design intended to capture variation among postulated causative factors for the disease (dustiness, coal rank, quartz content and ash content).
The massive scale of the study is revealed by its population size: >30000 chest radiographs taken and classified in the first round of medical surveys alone. Because it was a prospective study, records of time worked by the study subjects were accumulated on a frequent and on-going basis, requiring a huge clerical and computational effort. At the same time, the systematic collection of industrial hygiene data began for each mine. Fay and Rae (1959) note 14000 shifts sampled, comprising 60000 individual measurements. To do all this work, the same report says that 19 people were engaged on medical data collection activities, 98 on the environmental side, and over 20 employed on other scientific and clerical activities.

In the late 1960s, the PFR undertook the ISS on selected coalface workers who had participated in the first, second and third medical surveys at 20 of the mines. The initial and final radiographs were read side-by-side for incidence and progression of disease over the roughly 10 yr interval between surveys. At the same time as the radiographs were being classified, the massive task of summarizing the industrial hygiene data continued, with final conversion to gravimetric dust concentrations derived using extensive data from side-by-side particle-count and gravimetric samples. Mine-based indices of CWP incidence and progression over the 10 yr were correlated with mine-based estimates of dust concentrations for coalface workers over the same period. Finally, these findings were probabilistically extrapolated to a 35 yr working life. These detailed data allowed the PFR researchers to quantitatively answer the question of how the risk of developing simple CWP was related to coalmine dust level and composition.

The following describes some of the particularly noteworthy aspects of the data and methods employed in, or applicable to, the ISS analysis.

DATA QUALITY

Data quality control was paramount in the PFR, and challenges were faced with both the exposure and medical data. The large scale of the operation mandated that many individuals had to be employed in data collection and processing, leading to the potential for inter-person variability and bias. The study was innovative in recognizing these concerns, designing methods for detecting and characterizing variability, and developing methods to optimize the precision and quality of the data. For example, the dust measurements were for many years obtained by particle counting (although the scientific evidence favored gravimetric sampling, no suitable gravimetric instruments were available until after the PFR was well in progress), and to avoid systematic differences between the many technicians involved in microscopy, standardized inter-counter checks were undertaken on a regular basis (Fay and Rae, 1959). When it became apparent that the particle counts were being seriously underestimated by particle overlap, a scientific method was developed to provide suitable adjustment, and the original counts laboriously corrected (Rogan et al., 1967).

Similar quality control issues were encountered with respect to both inter- and intra-reader variation in classifying the many thousands of chest radiographs obtained from mines distributed across the country. To mitigate this situation, reader comparisons were undertaken periodically involving both PFR and National Coal Board PXR Scheme readers. The results were distributed to the readers, showing their differences from each other, and from themselves in previous readings, thereby facilitating reader agreement. The experience gained with reader variability has been critical to many other situations, such as the B-reader certification program of the US National Institute for Occupational Safety and Health (NIOSH).

METHODS DEVELOPMENT

Perhaps under-recognized is the innovative role of the PFR in the field of occupational epidemiology. The original investigators recognized the critical need for reliable quantitative exposure data; the study design reflects this emphasis, in both methods of data collection and analysis. Collection of quantitative data permitted comprehensive assessment of exposure–response, and also provided the opportunity for many other subsequent and diverse analyses (e.g. Tran and Buchanan, 2000).

Some of the major innovations came about in the industrial hygiene arena. Although sampling was routinely performed at that time in coalmines for dust control purposes, British National Coal Board scientists recognized that these data, generally collected in the dustiest areas or worst-case situations, were not appropriate for study of the relationship between exposure and disease (Hicks, 1952). Instead, detailed and representative information on job- and minespecific airborne concentrations (together with individual work histories) were needed to estimate each miners’ cumulative exposure accurately over a working lifetime. The procedure used the concept of uniform exposure groups (‘occupational groups’) within which ‘random colliers’ were selected for sampling and the results compiled into an average for the whole group of miners making up that group. (This was before the development of personal sampling devices that workers could wear to measure breathing-zone concentrations throughout the shift.)

This concept of dividing a workplace into ‘exposure zones’ for assessment of workers’ historical or current exposure is a fundamental concept in occupational hygiene today. Corn and Esmen (1979) were
among the first to formally publish a method to efficiently estimate and monitor exposures of all workers in industrial hygiene sampling programs, referencing Woitowitz et al. (1970) as the initiator of the concept of separating and ranking exposure zones within a facility. However, the development of this approach goes much further back, to the work of Oldham and Roach (1952). Employment of these concepts in the PFR was probably the first extensive use in occupational epidemiological research. In fact, by employing an ingenious, statistically derived sample allocation plan to optimize the benefits of the environmental effort while minimizing cost (Ashford, 1958), the PFR went well beyond the simple adoption of this occupational-group plan for sampling. As noted much later by Heederik and Miller (1988), optimal allocation minimizes attenuation in exposure–response coefficients.

In order to compute the lifetime risk of disease development—a critical need for input in setting an interim dust limit for British coalmines—Jacobsen and colleagues stochastically extrapolated the 10 yr exposure–response information to 35 yr working life predictions for various dust levels. These researchers realized that the Markov chain approach could be adapted for probabilistic modeling, based on a matrix of probabilities defined by initial and final radiographic category over the 10 yr, and conditional on dust level. Twenty years later Boult et al. (1991) proposed the combination of modeling and Markov extrapolation as a novel technique in forecasting.

**SIGNIFICANCE**

The findings from the Jacobsen et al. study provided one major message: control of CWP lay primarily in the simple reduction of levels of respirable coalmine dust. In this, gravimetrically based dust concentration was found to predict better than did particle count information. Moreover, the various components of the dust (e.g. silica and carbon content) were found to be of secondary importance compared to respirable mixed coalmine dust. The sine-squared model employed predicted a zero probability that a miner would develop CWP category 2 or greater after 35 yr of exposure of ~2 mg/m³. On this basis, 2 mg/m³ (MRE equivalent) was designated as the exposure limit over each full shift in US coalmines [measured using a size-selective cyclone sampler, but converted to concentrations equivalent to those obtained with the British Mining Research Establishment (MRE) sampler, as used later in the PFR]. A 3.4% probability was expected at approximately twice the concentration, 4.3 mg/m³. This concentration was adopted as a long-term mean value (represented by a daily limit of 8 mg/m³ in the return roadway) as the dust exposure limit for underground coalmines in the UK. Hence, based on these data, compliance limits in both Britain and the US were set on the basis of mixed coalmine dust levels. To a large degree, these limits have succeeded in dramatically reducing the prevalence of CWP in both countries.

**LESSONS LEARNED**

One important, though not immediately obvious, aspect of the exposure–response modeling in the Jacobsen et al. paper was the strong influence of the mathematical model chosen to predict the disease probability. This sine-squared model, employed and shown in equation (1) of the paper, is very similar in shape to other exposure–response curves employed today (e.g. logistic), but differs from many by permitting a threshold of disease (i.e. zero occurrence at non-zero exposure is possible). As noted above, the model predicted essentially zero risk of category 2 or greater at 2 mg/m³. Subsequent analyses by Hurley et al. (1982) and others in the PFR and elsewhere have used the logistic model, which does not assume a threshold; these later analyses naturally indicate higher disease probabilities at low concentration. (It should also be noted that the risk estimates from subsequent PFR studies were possibly also variously influenced by different miner selection criteria, longer follow-up periods and the inclusion of retired miners.) This example illustrates the difficulties faced by researchers in deriving predictions of effect at exposures that lie outside or toward the low end of the observed range of data, and the critical effect that choice of model has on those predictions. In this case, the implication was that the US dust limit was not as protective as originally desired; however, there were minor implications for the 4 mg/m³ British standard since the sine-squared and logistic models generally provided similar predictions in that exposure range. Overall, the fundamental importance of reducing dust exposure to reduce disease remains valid, as do the steps that were taken to implement dust control plans as a result of this research.

A second issue, which was studied further after the publication of this paper, was choice of study population. The ISS analysis was based on working miners in the dustiest jobs. This could have led to bias due to healthy worker selection. Studies that followed the ISS included miners in other jobs, as well as ex-miners. They were found to provide substantially similar predictions around the dust concentration at the British compliance limit (e.g. Hurley et al., 1982; Soutar et al., 1986). (Whether or not worker selection effects might have had implications for the US compliance limit is impossible to tell because the later analyses employed a different, and non-threshold, exposure–response model, the logistic curve.) Systematic interest in the effects of worker inclusion into (and selection out of) cohorts developed after the paper was published, and methods
have since been derived to assess such effects (e.g. Arrighi and Hertz-Picciotto, 1996).

A third issue arose from a basic assumption employed in development of the risk estimates of ISS study—that miners would be unlikely to develop progressive massive fibrosis (PMF) if they were protected from developing category 2 CWP. This assumption was based on early studies of PMF incidence (Cochrane, 1962; McIntosh et al., 1971). Later investigations discovered that PMF occurrence on a background of less severe simple CWP, or even no radiographically visible CWP, appeared to have been underestimated (Shennan et al., 1981; Hodous and Attfield, 1990). Thus, although it was true that miners with more severe simple CWP were at greater risk of PMF, the much greater number of lower-risk miners with less severe CWP led to relatively large numbers of PMF cases. This may be one factor in the continued occurrence of PMF among coalminers despite the lower dust exposure limits.

Finally, the ISS analysis was concerned with quartz exposure as it was routinely encountered in the mines. In this context, quartz average concentration was found to add little to the predictive ability of a cumulative exposure index based on mixed mine dust. [Coal rank was later found to be an important risk factor (e.g. Walton et al., 1977)] However, high disease incidence rates found in certain high-silica situations demonstrated the importance of quartz in the development of pneumoconiosis in coalminers (e.g. Seaton et al., 1981; Jacobsen and Maclaren, 1982). NIOSH has recommended the specific monitoring of respirable crystalline silica to provide more effective control of that highly toxic dust (NIOSH, 1995).

SUMMARY

Overall, the paper by Jacobsen et al. is not only a landmark in the study of coalworkers’ pneumoconiosis, but is a testimony to all of those who worked in the PFR. The scientific achievements of the PFR are extraordinary, especially when it is realized that it began when occupational epidemiology was in its infancy.

The paper was highly influential in occupational hygiene by providing the probabilistic basis for setting exposure limits for respirable coalmine dust, in the UK, the US, and other countries. Although the estimates were later revised in studies with longer follow-up and inclusion of retired miners, the fundamental conclusions remained valid. They provided the impetus for major changes in occupational hygiene practice in coalminers, which has led to a substantial reduction in occupational lung disease among coalminers.

REFERENCES


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