A Triangulation Approach to Historical Exposure Assessment for the Carbon Black Industry

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The determination of cumulative exposures for individual workers is necessary for research and practice of occupational health and hygiene. Reconstruction of exposures for a study of respiratory morbidity was needed to study the effects of exposure to carbon black production. Approximately 15,800 exposure estimates were needed. There were 22 plants, a 40-year time span, six job categories, and three types of dust-exposure metrics (respirable, inhalable, and "total" dust). Three information sources were used: 1) Industrial hygiene air level measurements where available (several industry-wide surveys had been conducted). 2) A formal process survey identifying specific dates and types of process and control changes. 3) An Historical Relative Exposure Rating Scale; plant health and safety personnel used this spreadsheet-based rating scheme to quantify exposures before and between years of actual measurement relative to a reference year in which measurements were available. A job-exposure matrix was calculated by integrating these three methods. Linear scaling factors were identified to interconvert geometric to arithmetic means and to interconvert total and inhalable dust. Individual worker cumulative exposures were then calculated based upon job histories linked with the job-exposure matrix. The nine-step process for integrating all available relevant data was effective in estimating the exposures for each of the cells of the job-exposure matrix. Among the 1680 workers participating, the mean cumulative inhalable dust exposure was 48.4 mg-years/m^3. Early years contribute disproportionately to the cumulative exposures of individuals since levels have declined significantly over time. The use of multiple sources of information, including a relative exposure rating instrument, significantly facilitates reconstruction of historical exposures. Inadequate adjustment for temporal trends can lead to underestimation of cumulative exposures and significantly affect estimation of dose-effect relationships. These methods are applicable to other situations requiring estimation of cumulative exposure with sparse industrial hygiene data in early years. (J Occup Environ Med. *2003;45:131–143*)

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Accurate and precise assessments of work exposure is a central component of occupational health and hygiene activity. Although advances in industrial hygiene and occupational medicine have significantly improved the ability to estimate current exposures for individual workers and for groups of workers, there are often significant uncertainties about past contaminant air levels. Nevertheless, exposure reconstruction is particularly important for epidemiologic research, evaluation of individual workers, program management, and legal reasons. Occupational epidemiologic studies of illnesses, such as cancers or pneumoconioses, rely upon cumulative exposure estimates. The selection of specific workers for intensive medical surveillance and counseling depends upon accurate assessment of individual risk, and program planning requires determining necessary resources for groups of such workers. Finally, equitable determination of causation for compensation purposes frequently rests upon assessment of antecedent exposures.

Marine navigation has traditionally used methods of "triangulation," in which location is determined by combining information from three different settings. This article describes a method for "triangulating" past exposures by integrating several distinct approaches. This work was conducted as part of a research project determining whether carbon black exposure produces significant respiratory morbidity.[1]

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TABLE 1
Standardized Job Titles

Code	Job Title
	Administration
ADO	Office/Management/Administrative/Technical/Other
ADP	Administrative with at least 20% in time
	Laboratory
LAB	Laboratory
	Maintenance
MIH	Instrument
MSH	In-Shop
MPL	In-Plant
MUT	Utility
MCL	Cleaner plant Crew
MFS	Maintenance Foreman (supervisor)
MEL	Electrician
MWF	Welder/Fitter
MJA	Janitor
MOT	Maintenance Other
	Production
PFO	Furnace Operator
PPL	Pelletizer
PSF	Foreman (supervisor)
PCO	Conveyor Operator
POT	Other
	Warehousing (Materials Handling)
WBP	Bagger/Packer/Sacker/Totes
WSB	Stacker
WGE	General Warehouse
WBL	Bulk Loader (railcar/trucks)
WFD	Forklift Driver
WSF	Supervisor
WUT	Utility
MOT	Material Handling Other
	Other
OTH	Other

Carbon black is widely used as a filler and pigment. Major uses include automotive tire materials, rubber products, and printing ink.[2,3]

Methods

The North American carbon black industry has conducted periodic routine health assessments of its workers, as well as industry-wide occupational exposure assessment campaigns in the recent past.[4–6] Researchers from the University of California, Los Angeles were asked to analyze these data to determine whether carbon black produces significant respiratory effects. To accomplish this, three distinct methods were used and then integrated to produce quantitative measures of cumulative exposure for individual workers. These three methods were 1) industrial hygiene air level measurements; 2) systematic survey of processes used; and 3) a quantitative relative exposure rating scale instrument. These were complemented by discussion with experts and plant site visits.

Standardized Job Titles

A standardized system for job titles was developed and is summarized in Table 1. Job titles are organized into a series of six major job categories: administration, laboratory, maintenance, production, warehousing (materials handling), and other. (Very few were in the latter category.) Each of these includes more specific job titles. A preliminary survey led to selection of this scheme to optimize 1) separation according to tasks; 2) applicability across plants; 3) applicability over time (ie, applicable to work histories in the past); and 4) consistency with other studies.

Air Sampling

Industry-wide sampling campaigns were conducted in 1979,[6] 1982–1983 (unpublished), 1987 (unpublished), 1993–1995,[4] and 2000–2001. All but the 2000 studies focused on the measurement of traditional total (37-mm closed-face cassette) and respirable dust. In addition, a side-by-side sampling project included concurrent sampling for inhalable and total dust fractions.[7] The most recent survey included 1010 inhalable dust samples and an equal number of respirable dust samples. Multiple plants and random employees/job titles were sampled to assure that results were representative.

Table 2 summarizes the previous air-sampling campaigns conducted in North American plants. As shown, although each of the sampling campaigns was systematic, they differed significantly. Most sampled total dust, some sampled total and respirable, whereas the most recent sampled respirable and inhalable dust.

The available level of detail differed; the early survey only provided information about broad job categories,[6] whereas others allow identifying information to the level of plant and job title within job category. Furthermore, some were summarized only by geometric means, whereas others had arithmetic means available. In addition, the 1995 survey intentionally did not sample the administrative job category employees on the premise that exposures were too low to warrant evaluation.[4]

Process Survey

The second component of the triangulation model was a formal process survey. Safety managers and/or senior engineering personnel completed a process history questionnaire. Each was encouraged to seek input from other employees as nec-

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TABLE 2
North American Carbon Black Manufacturing Exposure Assessment Campaigns, 1979–2001

Timeframe	Number of Companies	Number of Plants	Sample Types	Number of 'Total'/Inhalable Dust Samples	Data Available
1979-80	7	24	Respirable, 'Total'	1564*	GM
1982-83	6	17	'Total'	973*	no summary statistics available
1987	6	17	'Total'	577*	GM
1993-95	7	21	Respirable, 'Total',	1004*	GM & AM
2000-01	7	22	Respirable, Inhalable	1010	GM & AM

* Measured as 'total' dust. Converted to inhalable based on 2.97:1 inhalable to 'total' relationship. 'Total' = 37-mm closed-face cassette; GM = geometric mean; AM = arithmetic mean.

essary to respond to questions; for example, some spoke with long-tenure employees. The process survey asked specific questions, such as number and type of production lines, dates of major process changes, and types and dates of exposure controls. This provided information useful in validating the quantitative measures and in selecting optimal reference points.

Historical Exposure Relative Rating Scoring Instrument

The third triangulation component was developed to acquire historical exposure information from knowledgeable employees through a formal rating scheme. A designated plant representative rated relative exposures over time in his/her facility for each of the major job categories relative to a designated reference year. For example, "In comparison to 1975, for the Production Job Category in 1960 to 1964, how did the exposures compare to exposures in 1975 in your plant?" Two reference years were used: 1975 and 1995.

A spreadsheet (Microsoft Excel) response matrix was developed to facilitate respondent participation. Responses were obtained by marking a point on a vertical line. Each point corresponded to a relative percentage (eg, 130% of reference value, 75% of reference value). In addition, qualitative terms were aligned to allow anchoring of responses (eg, much higher, higher, similar, lower, much lower). Error checking was incorporated to alert the user to incompatible results (eg, entering two different values for the same time period). The spreadsheets were designed to be self-explanatory, but a verbal explanation was also provided by one of the investigators, who encouraged individuals to provide their best estimate even if empiric quantitative data were unavailable.

Expert Opinion and Plant Visits

The formal methods of historical exposure estimation were complemented by less structured approaches. Each plant was visited at least once by one or more of the investigators. The investigators spoke with employees, environmental control, and safety personnel.

Worker Job Histories

A systematic approach to obtaining job histories was used. Record systems and job titles differed from plant to plant, and therefore work histories were obtained from subjects directly rather than relying upon personnel records. A consensus set of job titles was selected, and those completing questionnaires were asked to use the most relevant job title, even if that title did not actually exist in the plant. Individuals could designate several different job titles for the same period of time

Development of Job-Exposure Matrix

The available data from the three structured methods (air sampling, process survey, Historical Exposure Rating Instrument) as well as the less formal information sources (expert opinion, plant visits, interviews) were systematically employed to create a job-exposure matrix. The historical job-exposure matrix had a row for each job category-plant-year combination. There were therefore >800 rows requiring data (40 years, 22 plants, six job categories). For each, exposure estimates were provided using three metrics, inhalable dust, 'total' dust, and respirable dust. Thus, 15,000 data estimates were required.

The process for populating each cell with data in the job exposure matrix is summarized in Table 3. It proceeded in the following steps.

1. Aggregate Averages. Empiric data can be summarized across groups of different size (eg, a single average for all workers or with averages for each plant). Based upon the available air sampling data, average information was calculated for all available levels of aggregation. "Aggregation" refers to the level of detail or fineness of the unit of analysis. This is frequently called the "granularity" of the data. Possible levels of aggregation include:

- Year: average of all values within a year.
- Job Category: average of all values within a job category for a particular year (eg, average for Production job category for 1988).
- Job Category-Plant: Average of all empirically measured values for a job category within a Plant (eg, for all Warehouse job category workers in the specified plant in 1995).

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TABLE 3
Exposure modeling method overview

1. Aggregate Averages
2. Estimate arithmetic means
3. Estimate all three of exposure metrics
4. Estimate exposures for each job category-plant combination for 1979, 1988, 1995, and 2000
5. Estimate unadjusted exposures for years without sampling data
6. Develop an historical weighting matrix
7. Estimate year adjusted exposures
8. Estimate cumulative for each worker for each year
9. Determine cumulative exposure for each subject

- Job Title: Average value for all within a particular job title, regardless of the plant (eg, all warehouse bagger-stackers in 2000).
- Job Title-Plant (eg, all bagger-stackers in the specified plant in 1988).

The availability of air sampling data for the more specific aggregation levels varied by year and by location. In 1979, information was available for all job categories, but only a limited number of Job Category-Plant dyads had data available. Measured exposure data were available only for the years 1979, 1983, 1987, 1995, and 2000. (The 1983 data were sparse and were not used in the analyses.)

2. Estimate Arithmetic Means. In some of the sampling campaigns, information was available only for geometric means (GMs) and not for arithmetic means (AMs). A multiplicative scaling factor was estimated by determining the arithmetic: geometric mean ratio in all situations for which both were available. (Although other methods for interconversion are available, they are distribution dependent, and many study summaries lacked adequate distribution descriptors, only recording the central tendency.) In summarizing the arithmetic:geometric mean ratios, extra weight was given to the empiric ratios available from the early years because exposures in these years would contribute the greatest amount to worker cumulative exposure. Thus, where a geometric but not arithmetic mean was available, the latter was estimated by multiplying geometric mean by the conversion factor.

3. Estimate All Three of Exposure Metrics. None of the sampling efforts included all three (respirable, total, inhalable) sampling methods. However, previous studies of one of the investigators incorporated extensive side-by-side sampling by the several methods. This allowed determination of an appropriate "scaling factor" to reliably interconvert between the total and inhalable metrics. However, the relationships between respirable and total (and therefore between respirable and inhalable) were found to be only weakly associated and nonlinear as the concentration of total dust increased.[4] This study focused on the relationship between inhalable and total, where scaling factors were shown to be consistent over a wide range of concentrations.[7]

4. Estimate Exposure for Each Job Category-Plant Combination for 1979, 1987, 1995, and 2000. For the years in which air sampling data were available, data were synthesized to estimate the exposures for every job category-plant combination. This was systematically conducted by using all available data. For example, where data were available to the level of plant-job category (ie, by job category within a plant) and job category (averaged over all plants), these data were combined; but when only job category data were available, this alone was used. Where both were available, a 1:1 weighted average was determined based upon the more broad and the more narrow measurements (reasons for this are provided in the Discussion section).

5. Estimate Unadjusted Exposures for Years Without Sampling Data. For most of the years covered (36 of 40) actual air sampling data were unavailable. For each of these years, an appropriate weighted average of data from sampled years was determined. (eg, in the 1960–1979 era, only 1979 data were relevant; however, in the 1980–1987 epoch, a weighted average of the relevant 1987 and 1979 exposure data were used).

6. Develop a Historical Weighting Matrix. The historical relative rating instrument provided an estimate of relative exposures for 5-year blocks throughout the years of concern for each major job category. Each rating was assumed to apply to the midpoint of the 5-year blocks. Intermediate years were determined by linear extrapolation (eg, 1965 was estimated as the average of the ratings for 1960–1965 and 1965–1970). For each plant-job category-year cell, the value was estimated by averaging by job category alone and by job category-plant. (This is referred to as a 1:1 granularity level weighting). For the three plants not completing the survey, least square means methods were used to estimate the data based upon all other available data across all years for the plant not completing the rating instrument.

Thus, a matrix was developed that allowed systematically taking into account the change in levels in the years between actual sampling. For each year-plant-job category combination, this matrix contained the level of exposure relative to a year in which measurements were made.

7. Estimate Year Adjusted Exposures. In step 4 above, an unadjusted estimate of exposure for each year-plant-job category tuple was calculated. However, this did not account for the progressive trend in reduced levels over time. Therefore, the unadjusted value was multiplied by the relative weighing (from step 6). This produced an estimate for each of the

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TABLE 4
Summary of Air Level Data
A: Inhalable Arithmetic Mean Exposures to Carbon Black by Major Job Class and Exposure Assessment Campaign, 1979-2000.

Study Year (Number of Samples)	Inhalable TWA AM Values for Major Job Classes, mg/m³				
	Administration	Laboratory	Production	Maintenance	Materials Handling
1979 (1564)	na	na	na	na	na
1983 (973)	na	na	na	na	na
1987[A] (577)	0.53 (2)	3.15 (23)	7.70 (164)	3.62 (181)	6.40 (207)
1995* (1004)	ns	0.89 (144)	1.22 (321)	1.49 (289)	3.45 (250)
2000 (1010)1	0.35 (125)	0.86 (103)	1.18 (273)	1.34 (257)	2.70 (247)

* 'Total' dust TWA GM values converted to inhalable dust values based on 2.97:1 inhalable to 'total' ratio. na - arithmetic means not available, (*N*) = sample number, ns = not sampled.

B: Inhalable Geometric Mean Exposures for Carbon Black by Major Job Class and Exposure Assessment Campaign, 1979-2000.

Study Year (Number of Samples)	Inhalable TWA GM Values for Major Job Classes, mg/m³				
	Administration	Laboratory	Production	Maintenance	Materials Handling
1979* (1564)	0.03 (72)	0.12 (133)	1.31 (480)	1.75 (386)	4.31 (493)
1983* (973)	0.18 (4)	1.51 (85)	1.34 (273)	2.11 (363)	4.84 (248)
1987* (577)	0.06 (2)	0.59 (23)	1.34 (164)	1.07 (181)	2.11 (207)
1995* (1004)	na	0.59 (144)	0.42 (321)	0.65 (289)	1.13 (250)
2000 (1010)†	0.18 (125)	0.44 (103)	0.47 (273)	0.66 (257)	1.57 (247)

* 'total' dust TWA GM values converted to inhalable dust values based on 2.97:1 inhalable to 'total' ratio.
† includes 5 unclassified samples not assigned to job classes, (*N*) sample number, na - not available

15,840 cells in the job exposure matrix, avoiding the assumption about linearity of decline over time.

8. Determine Exposure for Each subject For Each Year. Information from the previous step was used to assign the exposure for each subject for each year by looking up the estimated exposures for relevant year-plant-job category in the job exposure matrix. This value was adjusted for the number of months the job was held in the year.

9. Estimate Cumulative Exposure for Each Worker. The cumulative exposure for each worker was determined by summing exposures for each year. In essence, this approach used all available data to develop the most precise and accurate possible estimate of cumulative exposure of each worker.

Results

Air Levels

In the early years, the bulk of the data available was for relatively coarse aggregation levels (eg, for broad job category rather than data for more detailed subunits characterized by specific job title and plant), whereas in more recent years, a finer level of detail was available. Available information about air level measurements is summarized in Tables 4A and 4B. The arithmetic mean: geometric mean ratio, calculated in those situations for which both could be obtained, averaged slightly below 2.0. There was a temporal trend, such that the ratio was higher in the earlier years.

Results of Process Survey

Considerable information was acquired from the formal process surveys. Table 5 includes examples of process changes identified by respondents and technology changes reported in published reports and literature. Although channel black plants were only a small part of production by the mid-1960s and are not part of any North American exposure assessment, they help mark the beginnings of a transition toward improved industrial hygiene controls as a result of the significantly more efficient oil furnace process. Additional significant declines in exposure values were seen again in the mid- to late-1980s. From the 1983–1987 era to the present, significant declines in average exposures for warehousing, maintenance, and production personnel can be observed.

Before the mid- to late-1980s, exposures were considerably higher. Warehousing-related exposures were probably most affected by the addition of dedicated local exhaust ventilation and by the shift to large container bulk shipping methods that evolved through the late-1970s and into the 1980s. Exposure concentrations for Warehousing operations decreased by more than 50% (GM) between 1979 and 1987 and by an additional 25% (GM) between 1987 and 2000 in North America. Significant declines in measured exposures again occurred between 1987 and 2000 for Production (AM, 85%; GM,

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TABLE 5
Process Changes in North American Carbon Black Manufacture Affecting Occupational Exposure, 1960–2000

Decade	Process Changes	Comment
1950–1960	1956 Oil-furnace reactor technology begins replacement of gas-furnace production.[20]	-Bureau of Mines survey of channel black plant.
	Oil furnace reactors are gas tight enclosures.	-Mean of 36 samples: 28.8 mg/m3
	Filter bag collectors begin replacement of cyclone and precipitator collectors.[21]	-28 samples > 6 mg/m3
		-6 samples < 3.5 mg/m3 -sampling methodology unknown.[22]
1960-1970	Agglomeration technology improves capture efficiency of carbon black.[2]	
	1965, channel black ≈6% of U.S. production, only 5 plants.[21]	
	Low yield gas-furnace process ceases production in 1960s.	1965 ACGIH proposes carbon black TLV.
	By mid-1960s over 95% of carbon black produced in closed oil-furnace reactors.[21]	
	Bulk shipping increases: railcar, 'super sack'.	
1970-1980	Industry-wide reactor and burner improvements increase efficiency.[2]	-OSH Act 1970
	1976 last channel black furnace in U.S. ceases production[3]	1972–1977 OSHA inspections evaluate 82 manufacturers and users:
	Most plants paved to facilitate housekeeping wash down.	20% of samples > 3.5 mg/m3, 60% of these exceed PEL by 1-2X.[23]
	Local exhaust ventilation for warehouse operations initiated.	1979 first industry-wide exposure survey of North American carbon black manufacturers.[6]
1980–1990	Laboratory operations provided with exhaust ventilation.	
	Most product shipped by bulk: railcar, totes, super sacks	
	Vacuum cleaning increases.	
	Pulse-jet collectors replace less efficient bag collectors	
	Automatic bagging and palletizing reduces bag handling.	
	Formalization of safety and IH programs.	
	Separate ventilation systems for warehousing.	
1990-2000	Vacuum bagging increases	This technology currently employed by approximately 10 of 22 carbon black plants in the U.S.

65% reductions) and Maintenance (AM, 63%; GM, 44% reductions) job categories.

Historical Exposure Relative Rating Summaries

Figure 1 summarizes the historic ratings of exposures. The figure shows exposure estimates that are expressed relative to a reference time, rather than as an absolute air concentration. There were progressive declines in overall exposure levels within the industry.

However, the effect was inhomogeneous across job categories. The decline was much greater for Production and Warehousing (Materials Handling) than for Administration and Laboratory. The reference periods were intentionally overlapped, and the data demonstrate that there was consistency between the values referenced for 1975 and those for 1995.

Job Exposure Matrix

As applied, the method produced estimates for exposure for >15,000 job category-plant-year-exposure metrics combinations. These are illustrated in Fig. 2, which shows results for total dust. Values are aggregated for each job category-year combination (ie, the results shown are averaged over all plants). The rate of decline differs from strict linearity, and changes over time vary according to the job category. Further, there are no major discontinuities at the years for which actual air sampling data were collected.

Worker Exposure Profiles

The worker exposure profiles are summarized in Tables 6a and b. Results are shown for the industry as a whole and by major job category. The table shows that the subject population and plants had differences in the cumulative exposures. For example, for estimated 'total' dust, this ranged from 8 to 21 mg-years/m^3.

Importance of Early Exposures

The importance of early exposures is summarized in Figs. 3 and 4. These figures are based upon the subjects participating in the morbidity survey; therefore it only includes individuals who were still working in the year 2000. Figure 3 shows the number of mgyears/m^3 of total exposure acquired by the population in

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each year. (eg, 3 current workers with average exposures of 2.0 mg/m^3 total dust in 1970 would contribute 6.0 mg-years/m^3 of total dust to the population dust burden for the year 1970). Figure 4 expresses the same information for each year as the cumulative of population dust burden. It is expressed as the proportion (percentage) of the total population burden acquired by the year 2000. In addition, the total person-years of work are shown in Figs. 3 and 4. Figure 3 expresses the person-years in absolute terms, whereas Fig. 4 expresses this in terms of the percentage of cumulative total.

The figures demonstrate that a disproportionate amount of exposure was acquired in the early years. For example, 50% of the exposure had been acquired by the year 1986, whereas only 31% of person-years had accrued by that time. Hence, early years contributed a very large proportion of the cumulative exposure to the current workers. As discussed earlier, this is consistent with the trend of significant declines in measured exposures beginning in the mid-to-late-1980s.

Discussion

The health effects of many dusts are related to cumulative exposure acquired over a working lifetime. Assessment of exposures, from the early years of many workers' careers, is particularly important for cancer studies and for studies of many occupational lung diseases. Unfortunately, such information is often not explicitly available. Our recent morbidity study of the North American carbon black industry[1] provided the stimulus for developing a method for optimally using as much available data as possible.

Extensive industrial hygiene studies of current plants are often ineffective in adding information for several reasons. First, current exposures are often markedly different from those in the past. In this industry, for example, average inhalable dust exposure for warehousing in the late-1970s was 4.35 mg/m^3 (1.45

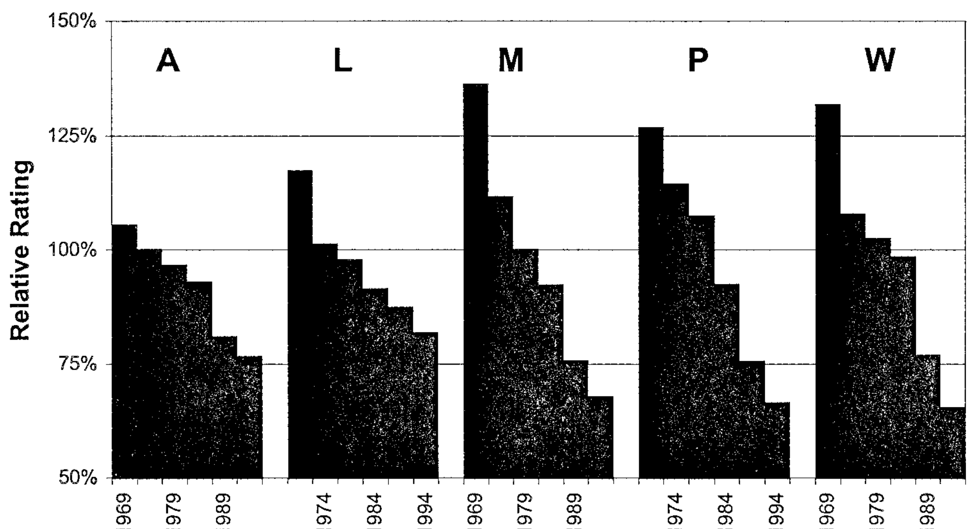

Fig. 1. Historic ratings of relative exposures. A = Administrative; L = Laboratory, M = Maintenance; P = Production; W = Warehouse.

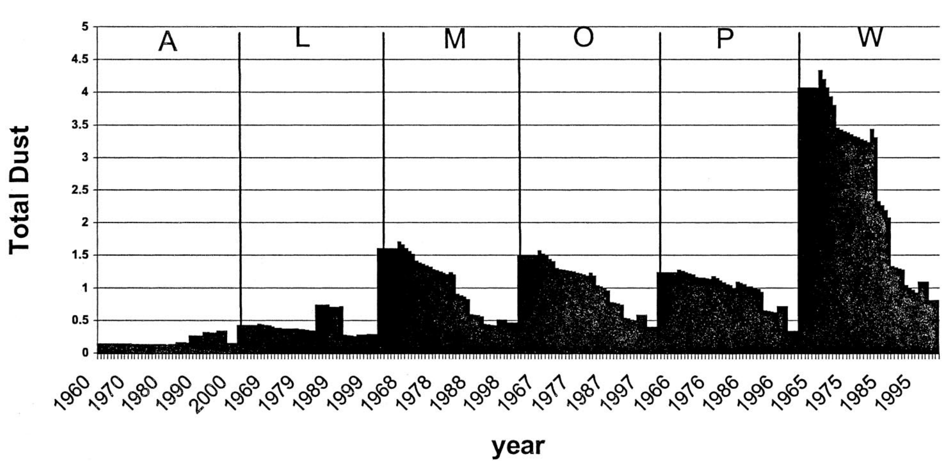

Fig. 2. Estimated typical exposures by year and job category. The figure shows the average exposure by year for each of the major job categories. The categories are defined in Table 1.

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TABLE 6
Worker profile exposure estimates

A. Exposure Estimates Overall

	Mean	(SD)	Range	*N*
Cumulative Inhalable	48.4	56.3	0.2–415.8	1680
Cumulative 'total'	16.1	18.8	0.1–138.6	1680
Cumulative Respirable	4.7	4.8	0.1–31.1	1680
Recent Inhalable	1.4	1.4	0.1–09.2	1680
Recent 'total'	0.5	0.5	0.0–03.1	1680
Recent Respirable	0.2	0.2	0.0–01.7	1680

B. Exposure estimates by major job category

	Cumulative Inhalable		Cumulative 'total'		Cumulative Respirable	
Job Category	Mean	(SD)	Mean	(SD)	Mean	(SD)
Administration	22.7	34.8	7.6	11.6	2.3	3.1
Laboratory	51.5	47.7	17.2	15.9	4.9	4.1
Maintenance	57.3	58.3	19.1	19.4	5.6	5.1
Other	62.2	92.9	20.7	31.0	5.5	6.9
Production	52.8	54.2	17.6	18.1	5.0	4.8
Warehousing	51.8	73.7	17.3	24.6	4.5	5.5

	Recent Inhalable		Recent Total		Recent Respirable	
Job Category	Mean	(SD)	Mean	(SD)	Mean	(SD)
Administration	0.4	0.6	0.1	0.2	0.1	0.1
Laboratory	1.0	1.0	0.3	0.3	0.2	0.1
Maintenance	1.5	1.4	0.5	0.5	0.3	0.2
Other	1.3	1.6	0.4	0.5	0.3	0.3
Production	1.3	1.3	0.4	0.4	0.3	0.2
Warehousing	3.1	1.6	1.0	0.5	0.4	0.2

Results are shown in units of mg-yrs/m^3 for cumulative and mg/m^3 for recent exposures.

total; GM), whereas it was 1.13 mg/m^3 (0.38 total; GM) in 1995. Second, where there has been a decline in the exposure levels over time, recent years have contributed disproportionately little to the cumulative exposure. For example, 5 years of warehousing related work at the recent 1.57 mg/m^3 (GM) inhalable exposure level contribute 7.85 mg-years/m^3, whereas five years work in 1979 (with exposure level of 5 mg/m^3) contribute 25 mg-years/m^3. Figures 3 and 4 illustrate that the assumption that employing industrial hygiene information acquired at the beginning of the study will lead to severe underestimation of the cumulative exposure. Third, particularly for studies of malignancy, latency increases the significance of exposure. Mortality studies are focused upon individuals no longer employed, creating even greater impact of estimates of early exposure. Hence, excellent current industrial hygiene studies have limited ability to improve precision of historical estimates.

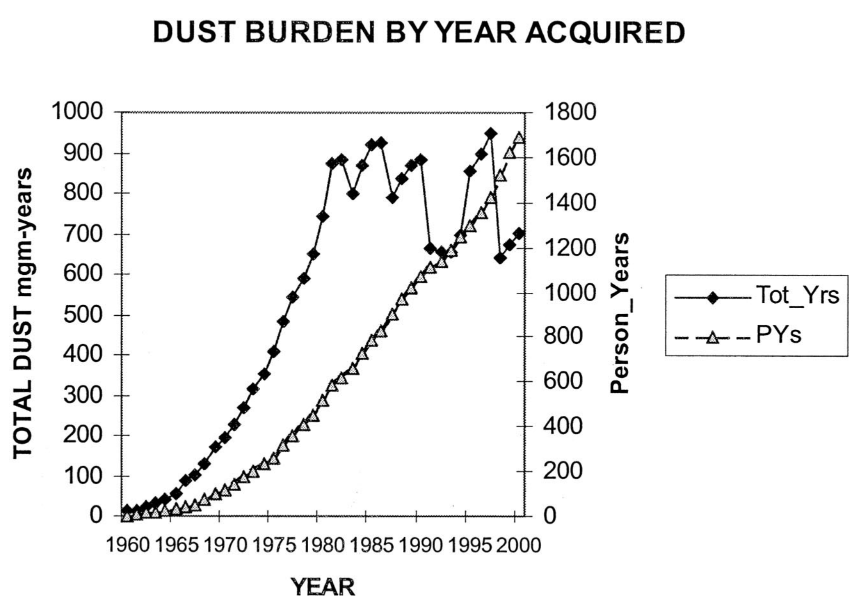

Fig. 3. Impact of early exposures on total population burden. The figure shows the number of person years of work (triangles) and the total dust burden (as mg-yrs/m^3 of 'Total' dust) acquired for each year. It is based only on workers currently employed in 2000.

Table 7 describes the challenges presented by the task of exposure reconstruction. The long duration of employment of many workers required assessing exposure for 40 years. There were twenty-two plants.

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A large number of individual job titles (approximately 45) that had been used in the industry were aggregated into five major Job Categories and one minor category. Three dust exposure metrics are employed (respirable, 'total', and inhalable). Thus, there are over 15,000 data points to be estimated in order to provide a job-exposure-matrix to cover the study population's employment.

Several methods for epidemiologic exposure characterization have been employed in prior studies of the carbon black industry. Early studies compared "exposed" individuals to "nonexposed" individuals without considering duration or intensity of the exposure[8] Subsequently, Kupper et al[9] characterized jobs as high or low dust and multiplied this by the number of years of work, producing a quantitative measure ("dust-years"). This depended upon a qualitative description and assumed that the current job was held for the working lifetime. Extensive studies were done by the University of Birmingham's Institute of Occupational Health. Initially (phase one studies), average lung function of members of six broad exposure groups was compared. The method assumed that each person within a job category had the same exposure and that recent air levels reflected those of the past.[10] In subsequent studies, this group further advanced methodology in two ways. First, exposures were assigned on an individual rather than broad group basis. Unlike earlier studies, in which the broad group mean was the unit of analysis, this permitted regression analyses of individual health outcome upon individual exposure estimates.[11,12] Second, follow-up industrial hygiene data were available, and it was possible to consider change in exposures over the course of the study. However, all exposures prior to the initial measurements were assigned to the value of 1987, even though qualitative data suggested exposures had been much higher.[13,14] They also did considerable theoretical analyses about the best way to combine individual versus group averages in

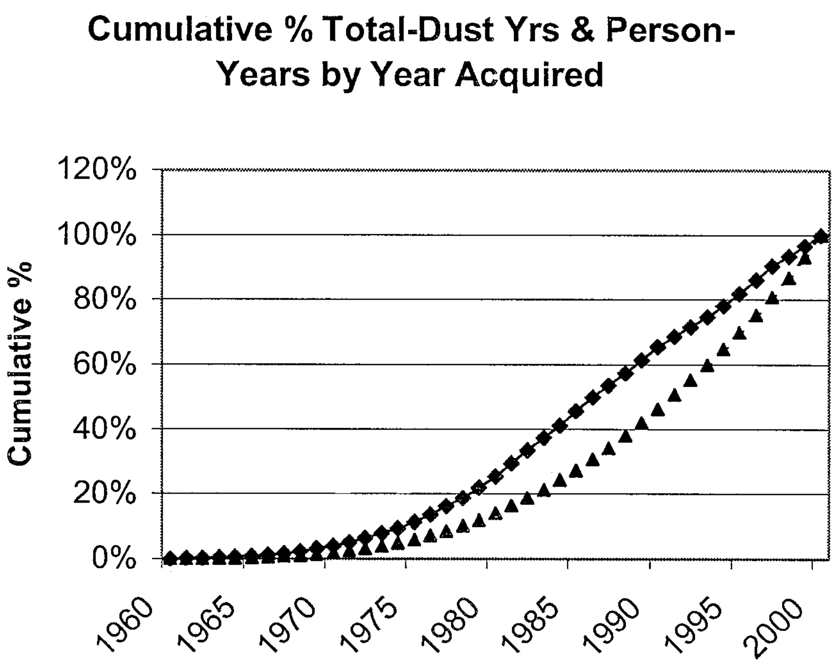

Fig. 4. Impact of early exposures on total population burden-cumulative % person years and exposure. The chart illustrates the cumulative exposure (as mg-yrs/m^3 of total dust; squares) and person-years of work (triangles) as percentage of total acquired.

TABLE 7
Challenges in Exposure Reconstruction

Challenge	Methods employed in other studies	Methods used here
Absent or limited air sampling data for most years.	1. Estimate based upon "expert opinion". 2. Back extrapolate 3. Assume most recent exposure measurements reflect all prior epochs.	Use several distinct data sources, including historical relative rating instrument, process survey, and expert opinion.
Varied exposure metrics (with 'total', inhalable, respirable size selective sampling, for example).	1. Use only data collected consistently over all times. 2. Interconvert using "standard" factors where available.	1. Empirically determine conversion factors using side-by-side measurements.
Differences in "granularity" (level of aggregation).	Employed most broad categories.	Aggregate to most specific data level available for each cell of job-exposure-matrix.
Use of geometric versus arithmetic means.	Use only industrial hygiene data for which raw data are available.	Calculate an empiric geometric: arithmetic mean conversion factor.
Temporal variability in jobs subject to sampling.	Use only data for which all jobs were sampled.	Use all available data.

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order to maximize the observed dose-effect relationships.[15,16] This is discussed further below.

The current study further extends these methods for exposure profiling in several ways. First, it allows integration of all available industrial hygiene data, not only information explicitly collected in conjunction with the research project. This is particularly important when the bulk of the exposure occurs prior to initiation of the research project itself. Second, it provides direct estimates of exposure prior to onset of the study, rather than assuming that all exposures were temporally homogeneous. Third, it provides a systematic approach for exposure assignment and extrapolation rather than relying upon simple averaging or linear extrapolation. Fourth, it explicitly integrates three distinct types of exposure information: measurement of air levels, process surveys, and a formal historical rating instrument.

General Design and Analysis Issues

There are several generic issues relevant in many retrospective exposure assessments described below.

Inclusion or Exclusion of Data. Even when industrial hygiene data from previous years are available, the methodology or the coverage of all work sites and job titles may be variable or incomplete. Hence, one must decide whether to exclude such information since it is not systematic. We elected to incorporate such information whenever available. However, the source of information was considered, and air level measurements designed to represent "worst-case" rather than typical exposures were excluded as potentially biased (eg, process upsets, spillage). This approach optimizes the use of sparse industrial hygiene data and avoids numerous assumptions for extrapolating recent data to previous years.

Level of Aggregation (Granularity). Next, it was necessary to select the appropriate level of detail of aggregation units for relating exposure to health outcome. For example, should workers be grouped simply into "exposed" and "not exposed," into broad job categories, by specific job title, by plants, or by more detailed combinations? Although the job exposure matrix allowed a finer level of detail, we elected to use intermediate level units, considering all combinations of year, plant, and broad job category for most purposes. Several factors influenced this decision: 1) Variance among units: The use of small or (more detailed) units is important only if this represents significant differences (eg, if differences among plants are quite small, aggregation by plants serves little purpose). 2) Specificity of work or assignment: Small "highly granular" job descriptive units are useful only if workers spend time exclusively in one unit without frequent crossover. For example, if maintenance workers frequently do both welding and carpentry, specific characterization of these job titles will not add precision to the ultimate goal of exposure profiling of the individual worker. (ie, While measurement of exposures separately for carpentry and welding is essential for implementing exposure controls, it does not add precision for epidemiologic study.) 3) Consistency across plants and time: To be useful, aggregation units must be meaningful in most settings. 4) Availability of data: If there are no data for a particular level of aggregation, it is advisable to use broader, less granular, units. 5) Number of workers in each cell: The size of the appropriate cell for analysis is also affected by the number of individuals involved and their affiliation to exposure.

Low-Exposure Jobs. Incorporation of exposure information about relatively low-exposure jobs is more important for epidemiologic purposes than for compliance monitoring. The statistical analysis model relating health outcome to exposure should guide the allocation of sampling resources. If categorical data analyses (eg, "low-," "moderate-," and "high-" exposure groupings (such as those used in the early University of Birmingham studies[10,17] are anticipated), precision of estimate within the lowest group is less important.. However, when regression analysis of health effect (y) on exposure as a continuous variable (x) is anticipated, the measurement of low exposures is particularly relevant. Indeed, for linear regression analysis, subjects with exposures at the extremes—both high and low—have considerably more influence upon the slope of the dose-effect relationships than do subjects in mid-range of exposure. Hence, for respiratory morbidity studies, in which linear models with continuous variables are commonly used, it is particularly useful to have precise measurements at the low end of exposure.

The data available for the current study illustrate the influence of the traditional bias against sampling low exposure jobs. For example, even the recent 1995 industrial hygiene survey did not extensively sample the administrative and laboratory job categories.[4] Because of this frequent bias, data may not be available for certain, job categories in any year.

Data Interconversions.

Measurement methods vary over time. Two types of data interconversions are necessary: 1) data based upon differences in air sampling methodology and 2) data caused by differences in statistical measures that had been used to summarize results. To allow use of industrial hygiene data from disparate sources, interconversion methods become necessary. (This is analogous to the need to interconvert change in exposure descriptions in the asbestos epidemiologic literature from measurements of millions of particles per cubic feet to fibers/cc and, more recently, from phase contrast microscopy to electron microscopy based methods). Similarly, in this study, interconversions among three size-related sampling techniques were necessary. Both temporal and geo-

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graphic factors affected the use of methods. Inhalable measurements were used in United States only recently, but were more widespread in Europe previously. To allow interconversion, we utilized conversion factors that had been delineated empirically in previous side-by-side sampling studies in this industry.[4]

When incorporating historical industrial hygiene data, raw data may be unavailable, and it is necessary to rely upon summary measures. Such measures typically include the mean and a standard deviation. However, these may be expressed either as the arithmetic mean and standard deviation or as the geometric mean and geometric standard deviation. The latter approach had often been used to control the influence of outlier samples. Therefore, a decision must be made: 1) Which is most appropriate for epidemiologic studies-arithmetic or geometric mean? and 2) How can geometric and arithmetic means be interconverted if some available data only includes one such measure of central tendency?

Biologic considerations suggest that the arithmetic mean is preferable when the effect is cumulative. In addition, this summary measure reduces the problem of exposure variation within job categories and within individuals.[18] The linear regression statistical model commonly used in respiratory morbidity studies implies that one mg-year/m^3 of dust exposure produces the same incremental decrement in forced expiratory volume in one second (FEV_1) whether the individual already has many or few accumulated mg years/m^3. We employed an empiric approach, determining the AM:GM ratio for each set in which both were available.

Inclusion of Data Other Than Air Sampling. Although air-sampling data were helpful, other exposure data also contribute. In this study, we used the "triangulation" approach of integrating two additional data sources: Process Survey, and the Historical Exposure Relative Rating Instrument. "Industrial hygiene expert opinion" is occasionally used for constructing job-exposure-matrices; this process, however, is often poorly specified and subjective. This study suggests methods for integrating expert opinion in a more structured manner. Many social sciences (eg, sociology) have demonstrated that consistent, quantitative survey data can be acquired even though the individual input unit includes subjective opinion.

Extrapolation Between and Before Empiric Data Points. Exposure data are often incomplete, not filling every possible job-exposure-matrix cell; technically, this is considered a "sparse" data set situation. Two analytic approaches may be used when data are sparse: 1) eliminating cells for which data are unavailable or 2) estimating the missing data. The former approach, eliminating the subjects or workplaces for which data are incomplete is not feasible in assessing cumulative exposure. In this study, for example, it would only allow incorporating individuals who began working in the year 2000, an obviously biased approach. Therefore, an estimation method is routinely used. One may assume all prior exposures were equal to current exposures (eg, in the Kupper et al[9] and the phase one Birmingham studies[14,17,19]). Alternatively, in years for which exposure data are unavailable, average (or extrapolate linearly) from the first previous year and first subsequent year for which data are available may be used. This assumes homogeneity of change over time and, in addition, relies extensively on data from two specific points.

A mathematical function may be fit to all available data points (eg, 1979, 1988, 1995, and 2000) and used to calculate those that are missing. Based upon the phase one/phase two industrial hygiene data of the European study, Gardiner hypothesized that an exponential model would be appropriate, with an exposure doubling time of approximately three years[19]. However, as in this industry, data often are too sparse to meaningfully select the appropriate model (eg, exponential versus linear) and to estimate its parameters. This also assumes that a single function can describe change across time without significant discontinuities (technically, assuming that the second derivative of the exposure-time equation exists at all points). However, significant discontinuities occur in the industrial setting (for example, installation of an exhaust system or a new production method).

In this study, we elected to use a decision rule oriented model rather than a mathematical equation model to estimate unmeasured values. A hierarchical rule system was employed: If available, data with the highest degree of specificity (ie, matching the year-job category-plant tuple) was employed. If not, in a specified order, the matching criteria were relaxed (eg, use data from the broader year-job category averaged across all plants

Cell Estimation—Combination of Values. Intuitively, more precise classification information would be expected to yield more precise exposure-health relationship information. However, exposure determination with very narrowly defined aggregation units (job title-year-plant), even if directly measured air sampling empiric data were available, does not optimize study results. As the exposure category definition becomes more precise (ie, of finer granularity), the estimate becomes less stable because of the smaller number of samples upon which the exposure is estimated. Van Tongeren et al. demonstrated both theoretically[15] and using empiric carbon black data[16] that significant attenuation of the exposure-response relationship occurs if industrial hygiene data for individuals are used directly. Defining units too narrowly will reduce the power of the study.

We sought to avoid such problems by two methods: First, we used an intermediate level of granularity (aggregating to level of broad job cate-

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gory, plant, and year, rather than to job title within the job category). Second, for each cell of the job-exposure-matrix, a weighted average was employed, giving equal weight to the most highly specific information where available (ie, job category-plant-year) and a broader category (eg, year-job category).

Validity Checking. An historical exposure reconstruction is nearly always less precise than assessment of current exposures. The use of multiple categories of information facilitates validity checking. Biases affecting each of the three information sources are likely to be different and orthogonal (independent). Hence, consistency across all three suggests validity, and use of the three information sources decreases the impact of error in a single one.

Industrial hygiene air sampling data are subject to several biases. Selection of samples for "worst-case" assessment or compliance evaluation rather than on a random basis for exposure characterization could systematically upwardly bias results. In addition, particularly in the past, relatively small numbers of samples were obtained. Precise gravimetric or chemical analyses of individual samples cannot compensate for interplant, interworker, and intraworker variability in actual exposure.[18] Although the precision of measurements may be very high for the sample itself, the estimate of exposure for narrowly defined exposure units may be unstable or biased.[15]

Process survey information also has limitations. Although it may pinpoint dates and locations of specific changes, these are not directly translated into actual exposure levels. Furthermore, worker exposure may have been strongly influenced by the "culture" of the plant rather than the presence or absence of specific process controls. Many experienced occupational health professionals understand the importance of the ethos of a facility about whether housekeeping is compulsively conducted, control equipment always maintained, and personal protection employed. The subjective component is poorly reflected in formal process questionnaires.

Historical exposure ratings, provided by "domain experts" themselves, may be subject to intentional or unintentional bias. While they can integrate the subjective component effectively, they provide no explanation. As is the case for process questionnaires, they also are not directly convertible into quantitative exposure levels, but rather provide relative values. They require some actual measurements to anchor the scale. Use of a formal instrument rather than informal "consensus" opinion can leave use bias. In addition, anchoring the qualitative estimates to actual air levels where available can facilitate conversion to quantitative, absolute metrics.

Despite the limitations of each of these methods, in concert they create a particularly powerful method for exposure reconstruction.

Implications

The European carbon black studies recognized the importance of underestimation of dust.[19] The slope of the linear FEV_1/mg/m^3 years relationship is often used as the basis of regulatory standard establishment. A 50% underestimation of cumulative exposure (eg, by applying recent data retroactively) could lead to 100% over-estimation of the effect. Extending the methods employed by Gardiner et al, we found that average exposures were approximately twice those estimated in the European study to adjust for exposures prior to study initiation. While the studies of Gardiner et al[10–12,17] are very effective in demonstrating the presence of a statistical relationship between cumulative exposure and reductions in FEV_1, the slope may be overestimated. In actuality the recent North American study[1]and the European study yielded compatible dose-effect slope estimates if one considers the underestimation of cumulative dose in the European study.

Combining several methods strengthens exposure assessment. Navigators employed triangulation methods to carefully define location, relying on several distinct reference points. Analogously, employing three or more reference points strengthens the historical exposure assessment. In this study, we employed air levels, process survey data, and a historical exposure relative rating scale instrument. This triangulation method allows using all available data despite differences in metrics, summary methods, and unit of aggregation. In addition, the method is fully explicit, rather than relying upon "expert opinion" alone, which may be subject to subtle bias. Use of historical relative rating instruments facilitates quantitative estimation of exposures before any industrial hygiene air data were collected. The approach is robust to differences in underlying distributions and to differences in input data.

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