

Estimates of historical exposures by phase contrast and transmission electron microscopy for pooled exposure—response analyses of North Carolina and South Carolina, USA asbestos textile cohorts

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ABSTRACT

Objectives To develop pooled size-specific asbestos fiber exposure estimates for North Carolina and South Carolina asbestos textile plants.

Methods Airborne sample data and prior exposure estimates by phase-contrast microscopy (PCM) for the two cohorts were reviewed and compared. Estimates by transmission electron microscopy (TEM) for 160 membrane filter samples from all plant were pooled. Poisson regression models were developed to predict bivariate diameter/length airborne fiber size distributions based on independent categorical variables for fiber diameter, fiber length, plant, and exposure zone. The model predicted bivariate diameter/length distributions were expressed as the proportion of fibers in 28 size-specific cells and these data were used to calculate PCM to TEM adjustment factors in order to estimate fiber size-specific exposures for the pooled cohort.

Results Exposure levels in the North Carolina plants were in excess of 50 f/cc for many operations through about 1955 owing to lack of dust control measures in early years whereas levels in the South Carolina plant were generally less than 10 f/cc by about 1950. The Poisson regression models found covariates for plant department to be a stronger predictor of bivariate size proportions than plant; however, a plant effect was observed. The final Poisson models demonstrated good fit to the observed data.

Conclusions Consistent with early studies, fiber exposures in the North Carolina plants were much higher than in South Carolina plant. Use of the predicted size-specific TEM exposures by plant and department based on the Poisson model predictions should reduce exposure.

BACKGROUND

While asbestos fibre exposure concentrations determined by phase contrast microscopy (PCM) and integrated over a working lifetime are strong predictors of asbestosis and cancer risks within a given industry, differences in risks between industry sectors (eg, chrysotile mining versus textiles) have not been reconciled by the PCM method. The PCM method measures only a limited portion of the aerosol (ie, fibres with diameters >0.25 µm and >5 µm in length). Limitations of the PCM method suggest the need for additional epidemiological studies and analyses using a fibre

What this paper adds

- Asbestos exposure levels were much higher in North Carolina textile plants compared to the South Carolina plant, especially in earlier years.
- Transmission electron microscopy (TEM) data for four asbestos textile plants demonstrate that the vast majority of airborne fibres were less than 5 µm in length and a substantial fraction of fibres longer than 5 µm were too small in diameter to be detected by phase contrast optical microscopy.
- Poisson regression models to predict bivariate diameter/length distributions by TEM fit the observed data well and the strongest predictor was textile process, although some evidence of a plant effect was noted.
- Use of statistical predictive models of fibre size distributions by plant and exposure zone should help reduce noise in the size distributions and the resulting size-specific exposures and provide a stronger signal in the size-specific exposure—response analyses for the pooled cohorts.

size-specific exposure metric based on transmission electron microscopy (TEM), which can detect and measure the entire asbestos aerosol, including fibres <0.25 µm in diameter.

Two prior cohort studies of asbestos textile workers employed in mills located in North Carolina and South Carolina, USA have shown significantly elevated overall risks for asbestosis and lung cancer as well as strong exposure—response relationships using PCM exposure estimates.^{1 2} Although based on different statistical models, the risk of lung cancer appeared to increase more steeply in the South Carolina cohort compared to that observed in the North Carolina plants.² The quality of occupational histories and asbestos exposure data for the North Carolina plants was lower than for the South Carolina cohort.^{2–4} The reduced quality of the exposure data as well as the occupational histories for the North Carolina plants suggest a higher level of exposure misclassification, and this could partially explain the attenuated exposure—response pattern observed for the North Carolina plants compared to the South Carolina plant.²

In addition to exposure estimates by PCM, size-specific exposure estimates based on TEM were developed for both the North Carolina and South Carolina cohorts using the results of TEM analyses of archived membrane filter samples collected in these plants from the mid-1960s through the early 1970s.^{4 5} These size-specific exposures were used to investigate risks for lung cancer by fibre size among workers in both cohorts.^{6 7} Both studies found that exposures to longer and thinner fibres were more strongly associated with the risk of lung cancer; however, exposures to shorter fibres were also positively associated with lung cancer risk.

The studies of North Carolina and South Carolina textile workers are the first published studies to provide quantitative exposure estimates by TEM and to relate these exposure estimates to risks in exposed workers. These studies have a number of strengths including reasonable cohort size as well as numbers of lung cancer and asbestosis cases for analyses, good historical dust measurements going back to the 1930s, and availability of archived membrane filter samples for TEM analyses. While both studies attempted to analyse as many TEM samples as possible, these analyses were both expensive and time consuming and many more TEM results were available by department in the South Carolina plant compared to the three plants in North Carolina, resulting in more statistical uncertainty in the TEM size-specific exposure estimates for the North Carolina plants.

A primary objective of our ongoing investigations is to conduct pooled epidemiological analyses of the data from North Carolina and South Carolina asbestos textile worker cohorts in order to estimate lung cancer risks based on PCM and TEM exposures. For both cohorts, PCM exposure estimates were based on statistical models developed from air measurements and these estimates are contrasted and compared in the current manuscript. We also sought to investigate fibre size-specific exposures by TEM for the pooled cohorts and to reduce measurement error by combining data from both previous studies. This report describes the development and application of a predictive model for bivariate size distributions for the combined cohort and derivations of TEM size-specific exposures.

METHODS

For our pooled analyses of both cohorts, the exposure models and data were reviewed in detail and it was concluded that the lack of information concerning process and control changes over time for the North Carolina plants precluded meaningful modelling of the pooled PCM data. Such pooled analyses would lose the rich detail available for the Charleston, South Carolina cohort and would introduce more error. Due to these considerations, the published PCM exposure estimates for the North Carolina and South Carolina cohorts were deemed to be the best possible estimates of PCM fibres for each cohort.^{3 4} Methods and procedures used to estimate PCM exposures for the North Carolina and South Carolina cohorts have been published.^{3 4}

The TEM methods, data reduction procedures and protocols for derivation of size-specific exposure estimates for the North Carolina and South Carolina studies were the same.^{4 5} Briefly, bivariate diameter/length size distributions were estimated for each plant and exposure zone using TEM data obtained using a modification of the ISO direct transfer method, which enumerates fibres 0.5 µm in length or longer.^{5 8} The bivariate fibre diameter/length data by plant and exposure zone

(department) were then used to estimate size-specific TEM exposures based on the 'adjustment factor' method proposed by Quinn and described in more detail later in this report.⁹ The Quinn method 'adjusts' standard fibre concentration measures determined by PCM using size fractions from bivariate fibre size distributions determined by TEM. These 'adjustment factors' take into account the proportion of all TEM fibres counted by PCM as well as the distribution of TEM fibres by diameter and length, resulting in fibre size-specific exposures.^{4 5} We made no adjustments for theoretical biological activity of fibres of different sizes. The TEM fibre size distributions and PCM adjustment factors were calculated for 28 diameter and length categories by plant and zone. The PCM adjustment factors were then applied to the estimated PCM airborne fibre concentrations by plant, zone, uniform job category and calendar time, in conjunction with work history data, to arrive at TEM size-specific exposure estimates.

Regression models for TEM data

Raw data for all membrane filter samples analysed by TEM for the North Carolina and South Carolina plants were available for analysis. These samples included 83 samples from the South Carolina plant and 77 samples from three North Carolina plants.^{4 5} Detailed methods for conducting the TEM analyses as well as raw data reduction have been previously published.^{4 5} Briefly, for each sample, TEM counts of fibres and fibre bundles were used as in the original analyses.^{4 5} Structure counts for each sample included the results of three separate TEM analyses that were performed, based on fibre length, in order to increase the count of the less prevalent longer fibres and therefore achieve greater statistical precision of the bivariate size distributions. These analyses consisted of counting all structures, structures >5 µm and structures >15 µm. The first two tiers are included in the standard ISO method and the third tier was added to provide sufficient data on the longer structures to better characterise the entire size distribution.^{5 8}

In the TEM analysis, individual structures (fibre or fibre bundle) were counted and measured for fibre diameter and length (including individual fibre and bundle structures within dispersed clusters or matrices).⁵ Each TEM structure analysed was placed into one of 28 length-width categories based on four diameter (<0.25, 0.25 to <1.0, >1.0 to <3.0, >3.0 µm) and up to eight length (<1.5, >1.5 to 3.0, >3.0 to 5.0, >5.0 to 10, >10 to 15, >15 to 20, >20 to 40, >40 µm) categories.⁶ The necessity of measuring long fibre lengths required a TEM magnification of 10 000× for the >5 µm and >15 µm counting strata, thus the smallest fibre diameter that could be reliably determined across all strata was 0.25 µm. These fibre size data were analysed by plant and exposure zone. Exposure zones corresponded to textile departments and a common scheme was developed for the combined data file. These department groups are described in the online supplementary material. For comparability to data from North Carolina plants, data for all weaving operations and winding operations for the South Carolina plant were combined.

The TEM data consisted of counts stratified into diameter and length categories; therefore, Poisson regression models for count data were explored. The Poisson regression models for proportions of fibres for each combination of fibre diameter, length, exposure zone (department) and plant can be written as follows:

$$\{n_{pijz}/\text{offset}\} = e^{X*\beta}$$

Taking logs and rearranging terms:

$$\log\{n_{pijz}\} = X*\beta + \log(\text{offset})$$

where:

X is the vector of explanatory variables (x_1, x_2, \dots, x_t) for combinations of plant, exposure zone, diameter category and length category;

n_{pijz} is the count of fibres or fibre bundles in each strata by plant 'p' and exposure zone 'i', fibre diameter category 'j' and length category 'z'.

As can be seen from the derivation above, inclusion of an offset allows modelling of the proportion of fibres in each of 28 fibre diameter/length categories. The offset effectively becomes the denominator for the proportion and the coefficient for this parameter is set to 1.0 in the Poisson model. The offsets accounted for the variable number of structures counted for each combination of plant and zone. The offset also accounted for the truncated nature of structure counts for the $>5 \mu\text{m}$ and $>15 \mu\text{m}$ counting strata, where fibres had to meet minimum fibre length requirements to be enumerated. Details of the offset construction for each model are described in the online supplementary material.

Poisson models were fit with the outcome being bivariate fibre diameter/length proportions by exposure zone and plant. Independent variables included categorical variables for diameter category, length category, exposure zone and plant. Progressively more complex Poisson regression models were evaluated based on combinations of the independent categorical variables. For all models, covariates for fibre diameter and fibre length were entered as nested categorical variables. Likewise, exposure zone was nested within plant in all models, consistent with our prior multivariate modelling of PCM exposures.⁴ Nesting represents a hierarchical data structure in which smaller experimental units are grouped within a larger unit. In our example, length category is nested within diameter category; therefore, a different set of levels of diameter appears with each length category. Exposure zones also were nested with plant. Nesting allowed appropriate consideration of joint effects in the models.

The Akaike's Information Criterion (AIC) was used to compare models and likelihood ratio tests were used to compare nested models. Analysis of residuals was used to assess overall model fit and to identify influential observations. Poisson model overdispersion was investigated using the GENMOD deviance/DF criterion. Pearson correlation coefficients were used to compare observed and Poisson model-predicted bivariate diameter/length fractions. Observed bivariate diameter/length fractions were calculated using the raw data by methods previously described.^{4 5} SAS v 9.2, which provides AIC results for the GENMOD procedure, was used for all analyses.¹⁰

TEM size-specific exposures

Based on the adjustment factor method for PCM concentrations developed by Quinn *et al*,⁹ PCM adjustment factors were developed using the predicted bivariate diameter/length fractions from the final Poisson regression model. The PCM adjustment factor, when multiplied by the estimated mean PCM concentration by plant, zone, job and time period, results in fibre size-specific exposure estimates.^{4 5} The PCM adjustment factor by plant, zone, diameter category and length category can be expressed as follows:

$$\text{PCM adjustment factor}_{pijz} = [(F_{pijz})/(FPCM_{pi})]$$

where:

PCM factor $_{pijz}$ is the PCM to TEM conversion factor for plant 'p' and exposure zone 'i', fibre diameter category 'j' and length category 'z';

$FPCM_{pi}$ is the proportion of all airborne fibres measured by TEM that are actually counted by PCM ($>0.25 \mu\text{m}$ in diameter and $>5 \mu\text{m}$ in length) for plant 'p' and exposure zone 'i';

F_{pijz} is the proportion of all TEM fibres in plant 'p' and exposure zone 'i' that fall into fibre diameter category 'j' and length category 'z'.

Both parameters for the PCM adjustment factors were estimated from the final Poisson model. These PCM adjustment factors were then applied to the previously published PCM-based estimates of airborne fibre concentration for each plant in order to estimate fibre size-specific fibre concentrations by plant, department, job and calendar time period.³⁻⁵

Observed fibre size proportions and PCM adjustment factors were compared with the Poisson model predictions. Observed size proportions and PCM factors were calculated using the raw data by methods previously described.^{4 5}

RESULTS

Comparison of estimated PCM exposures by plant

Estimated mean exposures by job categories within textile departments are compared in table 1. Exposures experienced in the three North Carolina plants were much higher than in the South Carolina plant, especially in the initial operations of fibre preparation and carding. Fibre exposures for most operations in the North Carolina plants remained very high until establishment of the first permissible exposure limit by the U.S. Occupational Safety and Health Administration (OSHA) in 1971.

Poisson models for bivariate size distribution and PCM to TEM adjustment factors

A total of 38490 fibres or fibre bundles were included in the combined data set used to derive the Poisson regression model. Results of fitting progressively more complex models are presented in table 2. These data show much stronger effects for textile production zones as opposed to plant in the models; however, the plant effect was significant ($p<0.05$) after the zone effects were included in the models (model no. 6 vs model no. 5), which implies plant-specific differences that should be included in the model.

Based on AIC criteria as well as likelihood ratio tests for the nested models shown in table 3, the final Poisson model to predict bivariate diameter/length fibre size fractions by plant and exposure zone included the following categorical independent variables, where parentheses are used to show nesting of parameters:

$$\text{Bivariate Size Fraction} = f[\text{diacat}(\text{lencat}(\text{zone plant})) \\ \text{diacat}(\text{zone plant})]$$

where:

lencat is the fibre length category ($<1.5, >1.5$ to $3.0, >3.0$ to $5.0, >5.0$ to $10, >10$ to $15, >15$ to $20, >20$ to $40, >40 \mu\text{m}$);

diacat is the fibre diameter category ($<0.25, 0.25$ to $<1.0, >1.0$ to $<3.0, >3.0 \mu\text{m}$).

Table 1 Comparison of estimated phase contrast microscopy (PCM) exposures model predictions by textile department, plant and time period

Textile department	Time period	Plant predicted range of mean PCM exposures by job category* (fibres >5 µm/cc)			
		NC plant 1†	NC plant 3	NC plant 4‡	SC plant 5§
Preparation	1935	90.1–207.0	86.6–126.6	—	26.2–78.0
	1945	50.3–115.6	55.1–70.7	69.8–130.1	8.1–23.9
	1955	24.4–56.0	23.4–26.7	33.8–63.0	8.1–23.9
	1965	11.9–27.4	11.5–16.8	16.6–30.9	5.8–17.2
	1975	—	3.6–4.6	4.6–8.5	5.8–17.2
Carding	1935	131.4–226.6	123.3–170.0	—	10.8–22.8
	1945	70.4–126.0	68.9–94.9	70.0–256.1	5.3–11.0
	1955	35.5–61.0	33.3–46.0	33.9–123.9	2.4–5.0
	1965	16.7–29.9	16.3–22.5	16.7–60.9	2.4–5.0
	1975	—	4.5–6.2	4.6–16.7	4.3–9.0
Spinning	1935	45.7–83.1	33.5–62.9	—	4.8–8.2
	1945	25.6–46.4	18.7–35.1	94.7–97.1	4.8–8.2
	1955	12.3–22.5	9.1–17.0	45.9–47.0	4.8–8.2
	1965	6.1–11.0	4.4–8.3	22.5–23.1	4.8–8.6
	1975	—	1.2–2.2	6.2–6.3	4.8–6.2
Twisting	1935	53.4–96.0	34.0–118.3	—	24.6–36.0
	1945	29.8–53.6	19.0–66.1	96.0–136.5	5.4–7.9
	1955	14.4–26.0	9.2–32.0	46.4–66.1	5.4–7.9
	1965	7.1–12.8	4.5–16.7	22.8–32.4	5.4–7.9
	1975	—	1.2–4.3	6.3–8.9	5.4–7.9
Weaving	1935	18.0–22.1	70.3–124.5	—	2.7–30.6
	1945	10.1–12.4	39.3–69.5	50.2–67.4	2.6–8.2
	1955	4.8–6.0	19.0–33.7	24.3–32.6	2.6–8.2
	1965	2.4–2.9	9.3–16.5	11.9–16.0	2.6–8.2
	1975	—	2.6–4.5	3.3–4.4	2.6–8.2
Winding	1935	30.9–52.3	81.8–87.4	—	4.1–20.9
	1945	17.3–29.2	45.7–48.8	23.9–40.5	4.1–8.4
	1955	8.4–14.1	22.1–23.6	11.6–19.6	4.1–8.4
	1965	4.1–6.9	10.9–11.6	5.7–9.6	4.1–8.4
	1975	—	3.0–3.2	1.6–2.6	4.1–8.4

*Means represent means of exposures by job within each department for the specified time period. The values are based on modelled exposures.^{3,4} Data for some Charleston departments were combined as shown in table 1.

†NC plant 1 stopped asbestos production in approximately 1970.

‡NC plant 4 began production in approximately 1942 with only weaving and finishing operations.

§Ranges of mean exposures for job categories within each department and time period. Charleston exposure models included dichotomous covariates for changes in engineering controls, which are reflected in the data presented. NC, North Carolina; SC, South Carolina.

Model overdispersion was investigated using the GENMOD deviance/DF criterion. The final Poisson model had a value of 1.68; however, an alternative negative binomial model, which is often used to account for overdispersion in Poisson models, had evidence of underdispersion with a value of 0.69. Given that a Poisson distribution is typically used for variance estimates of particle count data, including

estimates of variability by the ISO TEM method used for this study, we chose the Poisson model over the negative binomial model and used a variance inflation factor of scale=deviance to account for a slight degree of model overdispersion.⁸

A high degree of correlation was observed between observed and model predicted bivariate diameter/length fibre size fractions. The overall Pearson correlation coefficient was 0.99 and

Table 2 Poisson regression model development based on Akaike's Information Criterion (AIC) and likelihood ratio criteria

Model number	Poisson regression model parameters	–2Log likelihood	Likelihood ratio test p value‡	Degrees of Freedom	Model AIC
1	Intercept only	100 401	—	867	124 874
2	diacat(lencat)* †	127 497	<0.0001	840	6265
3	diacat(lencat) zone	127 520	<0.0001	831	6238
4	diacat(lencat) diacat(zone)	127 591	<0.0001	804	6148
5	diacat(lencat) diacat(zone) lencat(zone)	127 827	<0.0001	741	5803
6	diacat(lencat) diacat(zone) lencat(zone) plant	127 831	0.0292	738	5800
7	diacat(lencat) diacat(zone) lencat(zone) zone(plant)	127 856	<0.0001	720	5787
8	diacat(lencat) lencat(zone plant)	128 262	<0.0001	600	5216
9	diacat(lencat) lencat(zone plant) diacat(zone plant)	128 463	<0.0001	510	4994

*Diacat is diameter category and lencat is length category. Fibres were placed into 28 categories of diameter and length for the Poisson models.

†Parentheses indicate nesting in the models.

‡Likelihood ratio test p value for new parameter added to those already in the model.

Table 3 Poisson regression model predicted and observed phase contrast microscopy adjustment factors for selected combinations of diameter and length

Textile department	Average for all plants combined	Plant predicted and (observed) adjustment factors			
		NC plant 1	NC plant 3	NC plant 4	SC plant 5
Fibres <0.25 µm in diameter and >5 µm in length					
Preparation	1.15 (1.08)	0.95 (0.75)	1.04 (0.69)	1.6 (1.91)	1.01 (0.97)
Carding	1.00 (1.04)	1.02 (0.84)	0.88 (0.88)	1.16 (1.39)	0.92 (1.03)
Spinning	1.41 (1.72)	1.08 (1.02)	1.07 (1.35)	2.08 (3.17)	1.40 (1.33)
Twisting	1.59 (1.43)	1.03 (1.05)	1.23 (1.11)	1.10 (1.48)	3.01 (2.06)
Weaving	1.35 (1.39)	0.96 (0.75)	1.40 (1.26)	1.36 (2.03)	1.67 (1.53)
Winding	1.21 (1.30)	0.93 (0.52)	1.04 (0.93)	1.75 (2.55)	1.14 (1.18)
Finishing and shipping	1.36 (1.40)	1.12 (0.92)	1.06 (0.88)	1.53 (1.38)	1.75 (2.43)
All fiber diameters and >20 µm in length					
Preparation	0.32 (0.30)	0.28 (0.25)	0.50 (0.41)	0.25 (0.28)	0.26 (0.25)
Carding	0.35 (0.36)	0.39 (0.36)	0.42 (0.42)	0.39 (0.44)	0.20 (0.21)
Spinning	0.51 (0.57)	0.51 (0.50)	0.42 (0.48)	0.58 (0.79)	0.52 (0.50)
Twisting	0.60 (0.56)	0.55 (0.55)	0.70 (0.66)	0.36 (0.43)	0.78 (0.60)
Weaving	0.49 (0.49)	0.64 (0.57)	0.61 (0.58)	0.35 (0.45)	0.38 (0.36)
Winding	0.41 (0.40)	0.62 (0.49)	0.26 (0.25)	0.35 (0.45)	0.41 (0.42)
Finishing and shipping	0.48 (0.45)	0.60 (0.54)	0.58 (0.53)	0.54 (0.51)	0.19 (0.24)
Fibres <0.25 µm in diameter and >20 µm in length					
Preparation	0.13 (0.10)	0.10 (0.05)	0.20 (0.11)	0.12 (0.12)	0.09 (0.12)
Carding	0.13 (0.14)	0.15 (0.12)	0.15 (0.17)	0.16 (0.19)	0.07 (0.08)
Spinning	0.24 (0.26)	0.21 (0.15)	0.17 (0.20)	0.33 (0.42)	0.24 (0.27)
Twisting	0.29 (0.23)	0.22 (0.16)	0.31 (0.23)	0.15 (0.21)	0.50 (0.34)
Weaving	0.22 (0.20)	0.25 (0.15)	0.28 (0.22)	0.16 (0.24)	0.19 (0.20)
Winding	0.17 (0.17)	0.24 (0.10)	0.10 (0.13)	0.18 (0.25)	0.16 (0.18)
Finishing and shipping	0.21 (0.20)	0.25 (0.20)	0.24 (0.22)	0.27 (0.27)	0.09 (0.12)

NC, North Carolina; SC, South Carolina.

the Pearson correlation coefficient for fibres >5 µm was 0.94. More information concerning Poisson model fit is provided in the online supplementary material.

Table 3 presents Poisson model predicted and observed PCM adjustment factors for various combinations of bivariate size fractions by plant and textile department. The observed PCM adjustment factors were calculated from the raw TEM data by plant and exposure zone as previously described.⁵ In general, predicted and observed PCM adjustment factors were reasonably close; however, there were some notable exceptions where predicted and observed factors were very different. For example, the predicted PCM adjustment factor for fibres <0.25 µm in diameter and >5 µm in length for the South Carolina twisting department was approximately 50% higher than the observed value calculated from the raw data. Additionally, the model predicted adjustment factor for spinning in North Carolina plant 4 was approximately 50% less than observed. Several of the predicted PCM adjustment factors shown in these tables differed from the observed calculated from raw data by 25% or more, with most of these occurring in North Carolina plants where fibre counts were more sparse.

DISCUSSION

Workers in the North Carolina asbestos textile plants experienced much higher fibre exposures compared to workers in the Charleston, South Carolina plant. Exposures in the North Carolina plants, while decreasing over time, remained substantially elevated until the first OSHA standard in 1971. The much higher exposure estimates for the North Carolina plants are consistent with the published studies by the U.S. Public Health Service (USPHS).^{11 12} The Charleston plant was studied by the USPHS in 1937 in an effort to document application of engineering controls to reduce asbestos exposures in textile plants. Page and Bloomfield stated in their publication concerning the

Charleston plant: "These results should not be interpreted as representing the maximum possible efficiency in the control of asbestos dust, but it is believed that they are representative of the best practice in this country at this time". A 1938 report on the North Carolina plants by Dreessen *et al* extensively discussed the Page and Bloomfield 1937 study and results for the Charleston plant under the heading 'The Control of Asbestos Dust', using the Charleston plant to demonstrate dust control methods for asbestos textile production.¹² Additionally, Page and Bloomfield presented results of studies at Charleston where ventilation systems were intentionally turned off to simulate conditions that would occur without the benefit of local exhaust ventilation. In the preparation department, dust exposures ranged from 2.4 to 6.7 MPPCF for all jobs with ventilation but increased dramatically to 59.6 MPPCF without local exhaust ventilation. Additionally, in the carding department exposures by job ranged from 0.8 to 4.6 MPPCF with exhaust ventilation of the carding machines but rose to 62.4 MPPCF without ventilation. The very high dust concentrations measured in fibre preparation and carding at Charleston without the benefit of local exhaust ventilation are consistent with the very high exposures measured by Dreessen *et al* in the North Carolina plants where dust control measures were applied far less.¹²

Poisson models to predict TEM bivariate size distributions demonstrated good fit to the raw data. Our choice of a Poisson model was motivated by a rather extensive literature that has used a Poisson distribution to estimate mean particle counts on filters and their variance. However, we also fit an alternative multinomial logistic regression model to these data. The estimated probabilities were nearly identical to those obtained by our Poisson model. However, the multinomial model was more overdispersed than our Poisson model based on the deviance/DF criterion, suggesting the assumption of binomial variability was not as good as the assumption of Poisson variability. Use of the

predicted size-specific TEM exposures based on the Poisson model predictions should reduce exposure misclassification and reduce associated attenuation of size-specific exposure–response relationships.

For the North Carolina plants, fewer fibres were counted for each plant and exposure zone combination compared to the South Carolina plant, resulting in lower observed counts and higher variability for some cells of the bivariate distribution, particularly for rare fibres such as those longer than 20 µm. For example, approximately 10% of the cells in the raw data bivariate diameter/length data for North Carolina plants had zero fibre counts, resulting in a PCM factor of zero based on calculations using the raw fibre data. While fibres of these size ranges are rare in these aerosols, their concentration is not zero. The Poisson model predicted bivariate fractions with zero observed fibres ranged from 0.0088% to 0.0491%. The Poisson model was thus useful in estimating these size fractions as well as PCM adjustment factors.

CONCLUSIONS

Workers in the North Carolina asbestos textile plants experienced much higher fibre exposure concentrations compared to workers in the Charleston, South Carolina plant. In addition, fewer samples were analysed by TEM for the North Carolina plants resulting in more statistical noise in the estimated size distributions compared to South Carolina. Poisson models were developed which fit the observed size data well and allowed better estimation of size fractions for very sparse categories such as fibres longer than 20 µm.

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