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Efficiency of different grouping schemes for dust exposure in the European carbon black respiratory morbidity study

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Abstract

***Objectives*—The aim of this study was to assess the theoretical efficiencies of different grouping strategies and its effect on the exposure-response relation in a study of respiratory morbidity associated with exposure to total inhalable and respirable carbon black dust.**

***Methods*—A large epidemiological study is being undertaken to investigate the respiratory health of employees in the European carbon black manufacturing industry in relation to exposure to carbon black dust. In phase 2 of the study, repeated measurements of total inhalable and respirable dust were taken which enabled estimation of various components of variability in the exposure data (within and between worker variance and within and between group variance). These variance components were used to calculate the contrast in exposure between the groups in various classification schemes and to calculate the theoretical attenuation of the exposure-response relation and the standard error (SE) of the slope.**

***Results*—High contrast in exposure was found when workers were classified according to the combination of their factory and job category as well as when these combinations were amalgamated into five exposure groups. Attenuation was minimal with most grouping schemes; only with the individual based strategy was the attenuation large. The SE of the theoretically attenuated exposure-response slope was smallest for the strategy based on individual people followed by the classification scheme based on factory and job category.**

***Conclusions*—It was concluded that, although some assumptions for the calculations of the attenuation of the exposure-response slope were not met, the most appropriate classification scheme of the worker seems to be by the combination of factory and job category.**

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Keywords: carbon black; exposure assessment; grouping strategy; attenuation

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Exposure-response analyses in occupational epidemiological studies rely heavily on the ability to distinguish workers with regard to the exposures of interest. In the past, workers have often been classified (either qualitatively or semiquantitatively) according to their task or job title. If quantitative data are available with repeated measurements on the same person, the estimation of the within and between worker and between group components of variability can give an indication of the homogeneity of the groups and the amount of overlap in exposure between them. The importance of estimating the different components of variability in occupational exposure data collected for epidemiological studies has been stressed by several authors.[1-4]

Currently, a large epidemiological study is being undertaken to investigate the respiratory health of employees in the European carbon black manufacturing industry relative to exposure to total inhalable and respirable dust. Carbon black is produced by the vapour phase pyrolysis of highly aromatic oils and low molecular mass aliphatic gases. Although there are minor differences in reactor design, in the main the process is uniform across the industry as are the tasks undertaken and the job titles. Also, all the factories in Europe produce carbon black solely and are not connected with any other production factories. It would therefore be reasonable to expect that exposure to carbon black would be similar across jobs and factories in the European manufacturing industry.

The epidemiological study was designed as several cross sectional phases which are being combined to provide a longitudinal element. So far, two phases have been completed.[5 6] In each phase, an extensive assessment of exposure was carried out.[7 8] In phase 2 of the study repeated measurements on the same worker were taken which enabled estimation of various components of variability in the exposure data (within and between worker variance and between group variance). Therefore, the analyses described in this paper were conducted only on the data from phase 2 of the study.

The efficiency of the different grouping schemes will be evaluated by comparing the contrast in exposure between the groups. Furthermore, the attenuation, which is the bias in the estimated exposure-response relation towards zero due to non-differential misclassification of exposure, and standard error (SE) of the slope of a hypothetical exposure-response

Table 1 Job categories and description

Job category	*Job descriptions*	K_P	K_{S_i}	K_{S_r}
1	Administrative staff, office bound, Administrative staff, non-office bound	651	35	41
2	Laboratory assistant, process control room operator (VDU/control room)	326	90	75
3	Instrument mechanic, electrician	185	88	60
4	Process foreman, furnace operator	287	101	82
5	Fitter, welder	222	80	46
6	Process operator, conveyor operator	375	105	77
7	Warehouseman, packer	243	111	68
8	Plant cleaner (non-office), site crew	77	32	38

K_P=Study population; K_{S_i}=monitored population for inhalable dust after restrictions; K_{S_r}=monitored population for respirable dust after restrictions.

relation will be calculated with recently developed equations.[9]

Methods

In phase 2, a total of 2366 workers participated from 19 factories located in seven countries.[6] All workers were classified into eight job categories (table 1). These job categories ranged from administrative staff (office and non-office bound) to warehousemen, and plant cleaners, which were expected to be those most highly exposed.

In total, 3601 total inhalable and 3013 respirable personal dust samples were collected. However, due to overloading (4.0%) and damage of filters (2.1%), only 3456 total inhalable and 2951 respirable dust measurements were available for analyses. Personal exposure to total inhalable dust was measured with the IOM total inhalable sampling head[10] with a flow rate of 2.0 $l.min^{-1}$. Respirable dust was measured with the SIMPEDS cyclone[11] with a flow rate of 1.9 $l.min^{-1}$. Filters, rather than the whole cassettes, were weighed, as it became apparent early in the study that the cassettes were easily contaminated on the outside by handling in the factory and in transit, thereby affecting the weight of the cassettes. Also, the very nature of carbon black means that remarkably little dust would be captured by the cassette. As this procedure was carried out for all samples no bias is thought to have occurred.

All the data were collected by factory personnel, who were trained by the research team. Also, factory visits were carried out early in the data collection stage to ensure compatibility of data collection between the factories. On receiving the samples, checks were carried out on the flow rate (deviations <10%) and whether the filters were damaged (n=50 and 23, respectively for total inhalable and respirable dust) or overloaded with dust (n=99 and 40, respectively). In cases where the sample was unacceptable, the factory was asked to repeat the measurement.

Repeated exposure measurements were available from 795 workers for total inhalable dust and from 648 workers for respirable dust. The measurements were taken randomly over a period of about 12 months. For the analyses only data from workers with repeated measurements and from those combinations of factory and job category with at least five workers with repeated measurements were used. After these restrictions and after excluding workers who had changed job during the sampling period, 1816 total inhalable dust measurements were available for 642 workers and 1291 respirable dust measurements for 487 workers (table 1).

Workers were classified into groups defined by factory, job category, and the combination of factory and job category. Also, five exposure groups were formed separately for total inhalable and respirable dust, by ranking all combinations of factory and job category according to the arithmetic mean exposure. Cut off points were chosen so that each group contained more or less equal numbers of study participants.

As the data were predominantly log normally distributed, the statistical analyses were carried out on the log transformed data with SAS System for Windows (Release 6.08, SAS, Cary, NC, USA). Nested one way analysis of variance (ANOVA) was carried out to estimate within (${}_{WW}S_y^2$) and between worker (${}_{BW}S_y^2$) components of variance,[12] although nested two way ANOVA was used to estimate the within (${}_{WG}S_y^2$) and between group (${}_{BG}S_y^2$) variability.[3] With the results of the nested one way ANOVA, the ratio of the 97.5th and 2.5th percentile of the distribution between workers (${}_{BW}R_{0.95}$) was calculated.[2]

Contrast (ε) in mean exposure levels between groups was calculated as described by Kromhout and Heederik:[3]

$$\varepsilon = \frac{{}_{BG}S_y^2}{({}_{BG}S_y^2 + {}_{WG}S_y^2)} \quad (1)$$

where:

ε = contrast in exposure between groups

${}_{BG}S_y^2$ = between group component of variance

${}_{WG}S_y^2$ = within group component of variance.

Possible values of contrast lie between 0 and 1, with a value of 1 indicating that there is no overlap between the groups and a value of 0 indicating that groups cannot be distinguished with regard to their exposure.

To calculate the attenuation and SE of the slope of the exposure-response relation, equations described by Kromhout *et al*[9] were used. The expected value of the slope can be estimated by:

$$E(\beta^\star) = \left(\frac{{}_{BG}S_y^2 + \frac{{}_{WG}S_y^2}{k}}{{}_{BG}S_y^2 + \frac{{}_{WG}S_y^2}{k} + \frac{{}_{WW}S_y^2}{kn}} \right) \times \beta \quad (2)$$

where:

β* = theoretically attenuated regression coefficient

β = true regression coefficient

${}_{WW}S_y^2$ = day to day component of variance

k = number of workers monitored per group

n = number of samples per worker.

Where the individual approach is used as the grouping scheme, the equation can be reduced to the one described by Cochran:[13]

$$E(\beta^\star) = \left(\frac{{}_{BW}S_y^2}{{}_{BW}S_y^2 + \frac{{}_{WW}S_y^2}{n}} \right) \times \beta \qquad (3)$$

where:

${}_{BW}S_y^2$ = between worker component of variance.

The SE of the slope for the group approach can be estimated by

$$SE(\beta^\star) = \sqrt{\frac{\frac{{}_{R}S_x^2}{k}\left[{}_{BG}S_y^2 + \frac{{}_{WG}S_y^2}{k} + \frac{{}_{WW}S_y^2}{kn}\right] + \beta^2\left[{}_{BG}S_y^2 + \frac{{}_{WG}S_y^2}{k}\right]\frac{{}_{WW}S_y^2}{kn}}{(G-3)\left[{}_{BG}S_y^2 + \frac{{}_{WG}S_y^2}{k} + \frac{{}_{WW}S_y^2}{kn}\right]^2}} \qquad (4)$$

where:

${}_{R}S_x^2$ = variance of the response variable

G = number of groups.

The equation for the SE of the slope for the individual approach can be derived from equation (4).[9] In using these equations it is assumed that the number of workers in each group is equal, that the number of repeated measurements is the same for all workers, that exposure data are available for all workers and that the health outcome is only determined by one exposure factor and no confounding factors are included in the exposure-response relation. Also, the day to day and the within group variance in the exposure data is assumed to be constant.

For the calculations it was assumed that the true slope of the relation between current exposure to total inhalable and respirable carbon black dust and decrements in lung function was −0.10 l/mg.m^{-3}, whereas the variance of the response variable (${}_{R}S_x^2$) was set at 0.15. Mean squared errors, which combine the effect of bias and SE, were calculated as follows:

$$MSE = (SE)^2 + (BIAS)^2 \qquad (5)$$

The calculations were carried out with Microsoft Excel (version 5.0c, Microsoft Corporation).

Results

The mean duration of sampling was 383 minutes for total inhalable (SD 87.3) and 381 minutes for respirable dust (SD 85.5). The mean total inhalable and respirable carbon black concentrations were 0.79 mg.m^{-3} and 0.36 mg.m^{-3}, respectively. After excluding workers without repeated measurements and factory and job category combinations as described previously, these mean exposures rose slightly to 0.92 mg.m^{-3} and 0.38 mg.m^{-3}, respectively. A *t* test showed a significant difference between the overall geometric mean concentration of total inhalable dust exposure of those workers included in and excluded from the analyses (geometric mean 0.44 mg.m^{-3} *v* 0.30 mg.m^{-3}, P<0.001). The slightly higher exposure after exclusion of workers and job categories is caused by the fact that less repeated measurements were collected from administrative staff compared with other job categories (table 2). No significant difference was detected for respirable dust exposure as relatively more measurements were available for administrative staff after exclusion of data.

Many combinations of factory and job category do not contain any data after the exclusions, leaving only 63 groups for total inhalable and 48 groups for respirable dust. For exposure to total inhalable dust, the highest mean exposures were found in job category 7 (warehousemen), with means ranging from 0.83 mg.m^{-3} in factory 2 to 3.0 mg.m^{-3} in factory 3. Other high exposures were found in some factories for job category 8 (plant cleaner, site crew) (mean 0.4–2.7 mg.m^{-3}) and in job category 6 (process operator, conveyor operator) (mean 0.3–2.1 mg.m^{-3}).

For respirable dust, the highest exposure levels were found among the warehousemen (job category 7), with the highest mean exposure found in factory 16 (mean 2.0 mg.m^{-3}). Also, a high average exposure was found for the instruments mechanics and electricians (job

Table 2 Inhalable and respirable dust exposure by job category, with all data and with only data from repeated measurements and restricting the data to factory specific job categories with more than four workers

	All data				*After restrictions*			
Job category	*n*	*AM*	*GM*	*GSD*	*n*	*AM*	*GM*	*GSD*
Total inhalable dust:								
1	517	0.27	0.15	3.1	79	0.29	0.13	4.1
2	514	0.37	0.23	2.9	241	0.42	0.25	2.9
3	437	0.63	0.36	3.0	271	0.65	0.39	2.9
4	491	0.57	0.29	3.5	298	0.57	0.29	3.5
5	358	1.08	0.61	3.4	209	1.12	0.65	3.2
6	532	0.93	0.51	3.3	338	0.98	0.51	3.4
7	456	1.68	0.86	3.7	297	1.78	0.93	3.8
8	151	1.33	0.60	3.6	83	1.40	0.73	3.5
Total	3456	0.79	0.37	3.7	1816	0.92	0.44	3.7
Respirable dust:								
1	497	0.19	0.10	2.9	110	0.17	0.10	3.2
2	497	0.21	0.13	2.6	243	0.19	0.12	2.6
3	302	0.37	0.17	3.0	147	0.43	0.19	2.7
4	406	0.35	0.19	2.9	176	0.36	0.19	3.1
5	295	0.38	0.20	3.1	123	0.41	0.18	3.6
6	389	0.35	0.19	3.2	194	0.30	0.16	3.2
7	394	0.69	0.33	3.1	185	0.76	0.33	3.4
8	171	0.56	0.26	3.1	113	0.43	0.23	3.1
Total	2951	0.36	0.18	3.1	1291	0.38	0.18	3.2

n=Number of samples; AM=arithmetic mean; GM=geometric mean; GSD=geometric SD.

Table 3 Variance components and contrast by exposure grouping scheme (total inhalable and respirable dust)

Classification scheme	$_{BG}GSD$	$_{WG}GSD$	$_{WW}GSD$	$_{BW}R_{0.95}$	ε
Total inhalable dust:					
Factory	1.73	1.96	2.71	14.0	0.40
Job category	1.73	1.98	2.71	14.6	0.39
Factory + job category	2.11	1.53	2.71	5.3	0.76
Exposure group	2.28	1.62	2.71	6.6	0.75
Respirable dust:					
Factory	1.51	1.54	2.77	5.4	0.47
Job category	1.43	1.61	2.77	6.5	0.36
Factory + job category	1.70	1.29	2.77	2.7	0.81
Exposure group	1.77	1.36	2.77	3.3	0.78

$_{BG}$GSD=between group geometric SD; $_{WG}$GSD=within group geometric SD; $_{WW}$GSD=within worker geometric SD; $_{BW}R_{0.95}$=median ratio of the 2.5th and 97.5th percentile of the between worker distribution; ε=contrast in exposure between groups.

category 3) in factory 3 (mean 1.3 mg.m^{-3}), although this was due mainly to one extremely high value.

Table 3 summarises the results of the nested two way ANOVA, showing the geometric SDs of the distributions between groups ($_{BG}$GSD), within groups ($_{WG}$GSD), and within workers ($_{WW}$GSD). The between group variance component is largest when the workers are classified by the combination of factory and job category ($_{BG}$GSD 2.11 and 1.70, respectively for total inhalable and respirable dust) or by exposure group ($_{BG}$GSD 2.28 and 1.77, respectively for total inhalable and respirable dust); the components of within group variance are relatively small for these two classification schemes. Table 3 also shows that the median ratio of the 97.5th and 2.5th percentile of the distribution between workers ($_{BW}R_{0.95}$) is lowest when the workers are grouped by the combination of factory and job category or exposure group. The highest contrasts were also obtained when workers were classified by factory and job category or exposure group. For total inhalable dust, the contrasts for grouping by factory and job category and exposure group were 0.76 and 0.75, respectively, whereas for respirable dust it was 0.81 and 0.78, respectively.

Table 4 shows the results of the calculations of the theoretically attenuated exposure-response relation and the SE of the slope of this relation. For these calculations the mean number of repeated measurements and the mean number of workers for each group was used. The attenuation for classification based on any grouping scheme is minimal. For total inhalable and respirable dust the attenuation was largest when grouping by factory and job category, with the attenuation being 5.6% and 11.8%, respectively. The attenuation was smallest when the workers were grouped by exposure group where the attenuation was 0.4% and 1.2%, respectively for total inhalable and respirable dust. Considerable attenuation of the exposure-response relation occurs when using the individual based strategy—that is, 32.6% and 53.5% respectively for total inhalable and respirable dust. Also, the 95% confidence intervals (95% CIs) do not overlap with the true exposure-response relation when using the strategy based on individual people.

In contrast, the predicted SE and the 95% CI of the slope are smallest for the individual strategy followed by the grouping scheme based on factory and job category. The mean squared error, which is a combination of the attenuation and the SE of the slope, is smallest for the grouping scheme based on factory and job category (table 4).

Discussion

This paper described the results of estimating the components of variability of exposure when different schemes of grouping workers (individual, job category, factory and job category, and exposure groups) were applied. The choice of the cut off points to form the five exposure groups was arbitrary and other grouping schemes could have been used, although it is unlikely that this will have affected the results to a great extent. These analyses were carried out to establish which grouping scheme would be the most efficient for a cross sectional analysis of an exposure-response relation between decrements in lung function and current exposure to total inhalable and respirable dust. We realise that decrements in lung function variables are often more closely related to cumulative exposure to dust, however, in phase 1 of the study, significant associations between current dust exposure and decrements in forced expiratory volume in one second (FEV_1) and 25%–75% of forced expiratory flow (FEF_{25-75}) were found.[5]

The estimated components of the exposure variance were used to calculate the contrast in exposure between exposure groups. Also, the attenuation and SE of a hypothetical exposure-response relation were calculated with the estimated variance components. This statistical

Table 4 Results of calculation of the attenuation and SE of the exposure-response slope for total inhalable and respirable dust (the true exposure response relation was set at −0.10 and the variance of the response variable at 0.15)

Classification scheme	G	k	n	ε	β*	SE(β*)	MSE x 10^{-3}	CI(β*)	
Total inhalable dust									
Factory	19	33.8	2.83	0.40	−0.0968	0.0296	0.884	−0.1547	−0.0389
Job category	8	80.3	2.83	0.39	−0.0986	0.0351	1.234	−0.1674	−0.0298
Factory (job category)	63	10.2	2.83	0.76	−0.0944	0.0203	0.442	−0.1341	−0.0546
Exposure group	5	128.4	2.83	0.75	−0.0996	0.0296	0.874	−0.1575	−0.0417
Individual	642	1.0	2.83	1.00	−0.0674	0.0149	1.284	−0.0966	−0.0383
Respirable dust									
Factory	16	30.4	2.65	0.47	−0.0932	0.0455	2.118	−0.1824	−0.0040
Job category	8	60.9	2.65	0.36	−0.0954	0.0605	3.682	−0.2139	0.0232
Factory (job category)	48	10.1	2.65	0.81	−0.0882	0.0321	1.169	−0.1511	−0.0253
Exposure group	5	97.4	2.65	0.78	−0.0988	0.0487	2.376	−0.1943	−0.0033
Individual	487	1.0	2.65	1.00	−0.0465	0.0207	3.293	−0.0871	−0.0059

G=number of groups; k=average number of workers in each group; n=average number of repeated measurements; ε=contrast in exposure between groups; β*=observed regression coefficient; SE(β*)=SE observed regression coeffient; MSE=mean square error; CI(β*)=95% CI of the observed regression coefficient.

approach has only recently been established in occupational epidemiology[1-3 9 12] and provides an objective means of evaluating the choice of original grouping schemes based on professional judgements.

Kromhout *et al*[9] published values for contrast in occupational exposure in several industries, by different grouping schemes. With reference to these industries, grouping by job category across factories in this study resulted in average contrast. When grouped by job and factory the contrast ranged from 0.21 in a study into exposure to electric magnetic field in the electric utility industry to 0.84 for exposure to styrene in the reinforced plastic industry.[9] Compared with these values the contrast when grouping by the combination of factory and job category resulted in relatively large contrasts in the European carbon black manufacturing industry (ε=0.76 and 0.81, respectively for total inhalable and respirable dust). This could have been due to the many factories and the fact that, in contrast with the studies reviewed by Kromhout *et al*, administrative staff, with low exposure levels, were included in the analyses.

High levels of contrast between the five exposure groups was not unexpected as the actual exposure data were used to form the groups. However, as a result of random measurement errors, the contrast would most likely be smaller if the same resulting exposure groups were to be applied to an independently collected data set from the same workers.

Only the factory and job category grouping scheme for respirable dust resulted in attenuation in excess of 10%. The attenuation for the individual approach, which by definition gives the largest contrast in exposure, was very large, 32.6% and 53.5%, respectively, for total inhalable and respirable dust. It is well known that the strategy based on individual people will be most efficient if the within worker variance is relatively small compared with the between worker variance.[9] However, in this study the within worker variance was larger than the between worker variance for both total inhalable and respirable dust, with the ratio of the within and between worker variance (λ) being 1.4 and 3.1, respectively. Unlike the strategy based on individual people, group based strategies hardly have any random measurement error (within worker variability)[9 15] and therefore the estimated exposure-response regression coefficients showed only minimal attenuation.

The SE of the slope was smallest with the individual approach and the factory and job category as the grouping scheme. The mean squared errors showed that the grouping scheme with the combination of factory and job category was least prone to the combined effects of attenuation and SE. It can be concluded that, based on the attenuation, SE of the slope and the mean squared error, the use of that grouping scheme was the most efficient of the ones presented in this paper for analyses of the exposure-response relation. Therefore, it was decided that in this study, the analyses of the relation between current exposure to total inhalable and respirable carbon black dust and the respiratory morbidity of the carbon black workers would use the classifications of workers by the combination of factory and job category.

It must be emphasised that this paper, although based on real exposure data, represents a theoretical example of the effect of grouping schemes on the exposure-response relation and that the result of these analyses cannot be generalised to other studies. In an attempt to reduce imprecision in the estimates of the variance components due to low numbers of workers and repeated measurements, resulting in unstable estimates,[14] only groups with five workers or more with repeated measurements were used for the analyses. This resulted in exclusion of about 48% and 56% of available measurements and 56% and 66% of all combinations of factory and job category, respectively for total inhalable and respirable dust. Therefore, the results presented here might not be representative for each worker, each factory, and each job category; and hence it is critical that in future studies of this kind, a sufficient number of workers are sampled repeatedly in each factory and job title combination. When all data were used to calculate the variance components, the between worker variance (individual approach) was somewhat lower for both total inhalable and respirable dust. Together with a lower average of repeated measurements for each worker this resulted in slightly raised levels of attenuation. Levels of contrast in exposure were slightly higher for the various grouping strategies when all data were used, with the exception of factory as the grouping scheme. For all grouping strategies the attenuation and the SE of the slope were less when all the data were used, due to the increased number of workers and measurements. The overall conclusions of the paper were, however, not affected by the exclusion of data.

The equations for calculation of attenuation and SE are based on a situation in which the health outcome only depends on the exposure factor without the presence of confounding factors. Obviously, respiratory morbidity will also depend on factors other than exposure, such as smoking, age, hobbies, etc. Also, as exposure data is predominantly log normally distributed, the calculation of the attenuation is based on the log transformed exposure data, whereas, in general, the exposure-response relation is estimated with mean exposure. Therefore, in theory the attenuation calculated in this paper applies to the relation between lung function decrements and log transformed exposure, which is a different exposure-response model from the one with mean values.

In the analyses, the assumptions were made that the within worker variance is equal across all individual people and that the between worker variance is equal across all groups. However, considerable differences between the groups in the within and between worker variances were found at individual group level. High levels of within worker variance could have been caused by the fact that the measurements were taken over a relatively long period (12 months) with possible undetected changes in the production process and climatic conditions and that considerable job rotation occurred in certain factories, increasing the variance within workers.

The ANOVA model used to estimate the various components of variability in this study only included random effects. However, if data were collected over a relatively long period or during multiple sampling periods, as is the case in this study in which data have been collected over two phases between 1987 and 1992, systematic changes in exposure might have occurred. Indeed, systematic changes in exposure have occurred between phases 1 and 2 of the carbon black study due to changes in the production process and implementation of control measures.[16] Future analyses of data collected throughout the various cross-sectional phases will study fixed effects as well as random effects to estimate the various components of variability. Calculation of cumulative exposure indices will incorporate the systematic changes in exposure over time.

Although it is not entirely clear what the effects are of violations of the assumptions on the results presented in this paper, we think that the results provide useful information on the efficiency of the different exposure grouping schemes. Based on these results, using all available data, exposure estimates for the combinations of factory and job category will be used in the exposure-response analyses. It is clear that more research, such as comparison of the results of the equations with exposure-response relations in real studies and simulation studies, is required to test the robustness of the equations.

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