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A COMPREHENSIVE EVALUATION OF WITHIN- AND BETWEEN-WORKER COMPONENTS OF OCCUPATIONAL EXPOSURE TO CHEMICAL AGENTS

HANS KROMHOUT,*† ELAINE SYMANSKI† and STEPHEN M. RAPPAPORT†

*Department of Air Quality, Wageningen Agricultural University, P.O. Box 8129, 6700 EV Wageningen, The Netherlands; and †School of Public Health, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, U.S.A.

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Abstract—A database of approximately 20 000 chemical exposures has been constructed in close co-operation between the School of Public Health of the University of North Carolina at Chapel Hill and the Department of Air Pollution of the Wageningen Agricultural University. A special feature of this database is that only multiple measurements of exposure from the same workers were included. This enabled estimation of within- and between-worker variance components of occupational exposure to chemical agents throughout industry.

Most of the groups were not uniformly exposed as is generally assumed by occupational hygienists. In fact only 42 out of a total of 165 groups (25%), based on job title and factory, had 95% of individual mean exposures within a two-fold range. On the contrary, about 30% of the groups had 95% of individual mean exposures in a range which was greater than 10-fold.

Environmental and production factors were shown to have distinct influences on the within-worker (day-to-day) variability, but not on the between-worker variability. Groups working outdoors and those working without local exhaust ventilation showed more day-to-day variability than groups working indoors and those working with local exhaust ventilation. Groups consisting of mobile workers, those working with an intermittent process and those where the source of contamination was either local or mobile also showed great day-to-day variability. In a multivariate regression model, environment (indoors–outdoors) and type of process (continuous–intermittent) explained 41% of the variability in the within-worker component of variance. Another model, in which only type of process (continuous–intermittent) had a significant effect, explained only 13% of the variability in the between-worker component of variance.

INTRODUCTION

THE importance of the within- and between-worker components of variability in occupational exposure has only been recognized recently (KROMHOUT *et al.*, 1987; SPEAR *et al.*, 1987; RAPPAPORT *et al.*, 1988). In reviews of methods for assessing exposure RAPPAPORT (1991a,b) summarized the variance components of occupational exposures in 31 groups of workers from nine types of facilities. Although these summaries suggested that both components of variance can be large, the database was too small to allow the results to be generalized. In order to overcome this problem a much larger database consisting of about 20 000 chemical exposures obtained from over 500 groups of workers in a variety of industries was developed. Since the exposures of all workers were measured by personal sampling on at least two occasions we were able to estimate the within- and between-worker components of variance. In this paper we will describe the database, summarize the variance components, and report on factors which contributed significantly to the variances including, type of exposure, type of industry, group size, type of measurement strategy, and production and environmental characteristics.

MATERIALS AND METHODS

The database consists of 83 sets of personal exposure data collected in 45 studies. The majority of the studies (58%) were performed either by or under the supervision of the authors. Some of the data were provided by other researchers (24%) and by industry (9%) and a few sets were extracted from the literature (9%) (LINDSTEDT *et al.*, 1979; COPE *et al.*, 1979; GOLLER and PAIK, 1985; HANSEN and WHITEHEAD, 1988). Results of half of the studies have been reported in the open literature (LINDSTEDT *et al.*, 1979; COPE *et al.*, 1979; GOLLER and PAIK, 1985; KROMHOUT *et al.*, 1987, submitted; SPEAR *et al.*, 1987; HANSEN and WHITEHEAD, 1988; HOLLANDER *et al.*, 1988; BOS *et al.*, 1989; MARQUART *et al.*, 1989; BURINGH *et al.*, 1990; KATEMAN *et al.*, 1990; GALVIN *et al.*, 1990; WATERS *et al.*, 1991; GEUSKENS *et al.*, 1992; PETREAS *et al.*, 1992; SMID *et al.*, 1992; YAGER *et al.*, 1993). The data within the database were collected over the years 1974–1989. Two of the authors (E. Symanski and H. Kromhout) elaborated the database, which comprises the variables listed in Table 1. Coding of the production and environmental factors was often done by consulting the original investigators. However, complete information on all variables was available for only about half of the groups. Workers were grouped by job title and by factory (location). The variance components were estimated for each group, having at least five workers with at least two measurements per worker. Thus, at least 10 measurements were required for each group. Measurements with an averaging time less than 4 h were excluded. Groups with more than 25% of their observations below the detection limit were also excluded.

TABLE 1. INFORMATION IN THE DATABASE

Variable	Description
Set	Unique number
Origin	Research group
Country	Country of origin
Factory	Unique number
Industry	Description of industry
Industry code	International Standard Industrial Classification (ISIC)
Job	Description of job
Job code	Original coding of job title
Class	Original classification of jobs (*a priori*)
Occupation	International Standard Classification of Occupations (ISCO)
Date	Date of measurement
Worker	Unique identity number
Type	Type of exposure (agent)
Exposure type	Physical characteristic (gas, particulate)
Concentration	Measured concentration
Detection limit	Below (=0) or at or above (=1) detection limit
Unity	Units of measurement (e.g. mg m^{-3})
Sampling time	Duration of measurement
Sample of workers	Non-random (=0); random (=1); volunteers (=2); everybody (=3)
Sample of days	Non-random (=0); random (=1); fixed days (=2); all days (=3)
Environment	Outdoors (=0); indoors (=1) (most of the time)
Local exhaust ventilation	Not present (=0); present (=1)
Process	Intermittent (=0); continuous (=1)
Mobility of worker	Stationary (=0); mobile (=1)
Mobility of source	Stationary (=0); mobile (=1)
Source	Local (=0); general (=1)

The analysis-of-variance (ANOVA) methods, which were used to estimate the components of variance, are described extensively elsewhere (RAPPAPORT *et al.*, in preparation). The fit of the ANOVA model to each group was evaluated with *ad hoc* procedures, based upon statistical methods to detect influential observations (CHRISTENSEN *et al.*, 1992) and to test the normality of the between-worker exposure distribution of log-transformed exposures (LANGE and RYAN, 1989). Details of our applications of these procedures are also described elsewhere (RAPPAPORT *et al.*, in preparation). Two of the authors (H. Kromhout and S. M. Rappaport) independently judged the goodness of fit of the ANOVA model for each of the groups and excluded either a worker or an individual measurement after consensus was reached.

The database exists as a SAS (SAS Institute, Cary, North Carolina, U.S.A.) data file which was created with DBMSCOPY (Conceptual Software, Inc., Houston, Texas, U.S.A.) out of several individual files created by Lotus-123 (Lotus Development Corporation, Cambridge, Massachusetts, U.S.A.), Excel (Microsoft Corporation, Redmond, Washington, U.S.A.), or SPSS-PC (SPSS, Inc., Chicago, Illinois, U.S.A.). Variance components were estimated from the log-transformed exposure concentrations employing the random-effects ANOVA model from Proc NESTED and the goodness of fit plots were made with Proc GPLOT and Proc GREPLAY using SAS System Software PC Version 6.04. The random-effects ANOVA model is specified by the following expression,

$$Y_{ij} = \ln(X_{ij}) = \mu_y + \beta_i + \varepsilon_{ij}, \quad \text{for } (i = 1, 2, \ldots, k) \quad \text{and} \quad (j = 1, 2, \ldots, n_i),$$

where

X_{ij} = the exposure concentration of the i-th worker on the j-th day,
μ_y = mean of Y_{ij},
β_i = the random deviation of the i-th worker's true exposure $\mu_{y,i}$ from μ_y, and
ε_{ij} = the random deviation of the i-th worker's exposure on the j-th day from his or her true exposure, $\mu_{y,i}$.

It is assumed under the model that both β_i and ε_{ij} are normally distributed; i.e. $\beta_i \sim N(0, \sigma_B^2)$, and $\varepsilon_{ij} \sim N(0, \sigma_W^2)$. The underlying distribution of exposures (X_{ij}) is assumed to be log-normal. Also, β_i and ε_{ij}, are assumed to be statistically independent of each other. Thus, the parameters σ_B^2 and σ_W^2 are referred to as the components of the total variance $\sigma_T^2 = \sigma_B^2 + \sigma_W^2$, and $Y_{ij} \sim N(\mu_y, \sigma_T^2)$. The estimates of σ_T^2, σ_W^2 and σ_B^2 will be designated as ${}_TS_y^2$, ${}_WS_y^2$ and ${}_BS_y^2$, respectively. From the variance components the standard deviations were estimated for the total (${}_TS_y$), within-worker (${}_WS_y$) and between-worker distributions (${}_BS_y$). These standard deviations were used to estimate the corresponding geometric standard deviations [${}_TS_g = \exp({}_TS_y)$, ${}_BS_g = \exp({}_BS_y)$ and ${}_WS_g = \exp({}_WS_y)$] and the ratios of the 97.5th and 2.5th percentiles of the log-normally distributed exposures of each group of workers (RAPPAPORT, 1991a,b). These ratios, designated as ${}_B\hat{R}_{0.95} = \exp(3.92\ {}_BS_y)$ and ${}_W\hat{R}_{0.95} = \exp(3.92\ {}_WS_y)$ provide information regarding the ranges of exposures experienced between workers and within workers, from day to day, respectively. The distributions of the within- and between-worker variance components were evaluated independently for several variables, including number of workers and measurements per group, type of measurement strategy, and production and environmental characteristics. Wilcoxon's rank sum test (SNEDECOR and COCHRAN, 1980) was used to test the significance of shifts of location in the distributions of total-, within- and between-worker variance components (Proc NPAR1WAY, SAS PC Version 6.04). Finally, a multivariate regression model (Proc GLM) was built to identify factors which contributed significantly to these variance components.

RESULTS

General characteristics of the database

In Table 2 the basic characteristics of the database are presented. Within the 45 studies 83 sets of measurements were collected from more than 3200 workers yielding almost 20 000 observations. The total number of groups based on job title and factory (location) was 522. The data originated mainly from The Netherlands (38%), the U.K. (38%) and the United States (20%). The majority of the groups were of Dutch origin (87%). The data sets from the U.K. and United States were generally much larger in terms of either workers in a group or measurements per worker. It is also clear from Table 2 that the majority of the data (76%) originated from several sectors in the chemical industry. The majority of the groups was also from the chemical industry (35%), but considerable numbers of groups were from the food (27%) and metal manufacturing industries (14%).

TABLE 2. BASIC CHARACTERISTICS OF THE DATABASE

Number of studies	45
Number of sets of measurements	83
Number of groups	522
Number of workers	3243
Number of observations	19 845

Country	No. of measurements	No. of groups
The Netherlands	7601 (38%)	455 (87%)
U.K.	7523 (38%)	5 (1%)
U.S.A.	4021 (20%)	59 (11%)
Sweden	592 (3%)	1 (0%)
P.R. China	108 (<1%)	2 (2%)

ISIC	Industry	No. of measurements	No. of groups
35	Chemical	15 028 (76%)	181 (35%)
351	Industrial chemicals	9409 (47%)	27 (5%)
352	Other chemicals	243 (1%)	21 (4%)
353	Refineries	2797 (14%)	22 (4%)
355	Rubber products	1962 (10%)	76 (15%)
356	Plastic products	617 (3%)	35 (7%)
31	Food	2014 (10%)	141 (27%)
38	Metal manufacturing	1266 (6%)	72 (14%)
37	Basic metal	510 (3%)	5 (1%)
32	Textile manufacturing	263 (1%)	32 (6%)
36	Brick manufacturing	243 (1%)	27 (5%)
71	Transport	227 (1%)	27 (5%)
95	Dry cleaning	171 (1%)	27 (5%)
34	Printing	115 (1%)	6 (1%)
11	Agriculture	8 (0%)	4 (1%)

The chemical agents are listed in Table 3. Over two-thirds (68%) of the measurements involved gases and vapours and about one-third (28%) involved particulate matter. Dermal exposures, measured with so-called pads carried on the lower parts of the wrists in two studies in the rubber industry, comprised only a very small part of the database (4%) (Bos *et al.*, 1989; Kromhout *et al.*, submitted).

Table 3. Agents present in the database

Agent	No. of observations	%
Gaseous	13423	67.6
Alkyl lead	176	0.9
Benzene	2409	12.1
Diphenyl	121	0.6
Diphenylether	195	1.0
Ethanal	43	0.2
Formaldehyde	131	0.7
Heptane	29	0.1
Hexane	29	0.1
Hydrogen fluoride	36	0.2
Mercury inorganic	592	3.0
Nitrogendioxide	137	0.7
Octane	37	0.2
Organic vapour	7523	37.9
Perchloroethylene	216	1.1
Styrene	617	3.1
Sulphur dioxide	36	0.2
Toluene	638	3.2
Total solvents	188	0.9
Trichloroethane	87	0.4
Trichloroethylene	55	0.3
Xylene	128	0.6
Gaseous and particulate	34	0.2
Total fluoride	34	0.2
Particulate	5519	27.8
Chromium inspirable	80	0.4
Copper inspirable	80	0.4
Copper respirable	110	0.6
Dust inspirable	2936	14.8
Dust respirable	276	1.4
Dust total	55	0.3
Endotoxin inspirable	669	3.4
Fluoride dust	36	0.2
Iron inspirable	80	0.4
Lead inorganic	177	0.9
Lead inspirable	79	0.4
Lead respirable	110	0.6
Nicotine inspirable	189	1.0
Quartz respirable	93	0.5
Welding fume inspirable	156	0.8
Zinc inspirable	283	1.4
Zinc respirable	110	0.6
Dermal	869	4.4
Pyrazofos	8	0.0
Cyclohexane soluble fractions	861	4.3

Exposure groups and variance components

Grouping the workers by job title and factory, and excluding groups, workers and individual observations based on the criteria mentioned earlier, left 165 groups with 1574 workers and 13 945 measurements. In Fig. 1 the distributions of the within- and

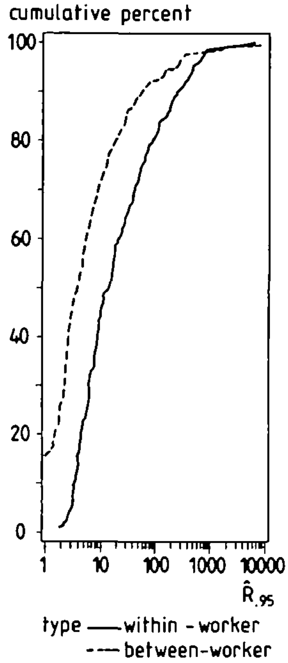

FIG. 1. Cumulative distributions of ${}_{W}\hat{R}_{0.95}$ (solid line) and ${}_{B}\hat{R}_{0.95}$ (dashed line) for all 165 groups of workers based on job title and factory.

between-worker values of $\hat{R}_{0.95}$ are shown for these 165 groups. Only 42 groups (25%) had 95% of the individual mean exposures lying within a factor 2 (${}_{B}\hat{R}_{0.95} \leq 2$). Almost 30% of the groups had values of ${}_{B}\hat{R}_{0.95} > 10$ and 10% of the groups had ${}_{B}\hat{R}_{0.95} > 50$. The day-to-day variability was generally larger than the between-worker variability, indicating larger differences in exposures between work shifts than between workers with the same job title and factory. The median values for the total, within- and between-worker geometric standard deviations were respectively, 2.41, 2.00 and 1.43.

Influence of group size and number of observations

In Figs 2(a)–(d) the influence of the number of measurements and workers on the distributions of the within- and between-worker values of $\hat{R}_{0.95}$ is shown. The influence of both the number of measurements and the number of workers in a group on ${}_{B}\hat{R}_{0.95}$ is negligible [Figs 2(a) and (b)]. However, the influence of sample size on ${}_{W}\hat{R}_{0.95}$ is significantly higher ($P < 0.05$, Wilcoxon rank sum test) for the groups with more measurements (more than 25) and more workers (more than seven) [Figs 2(c) and (d)]. The increase in ${}_{W}\hat{R}_{0.95}$ with number of measurements may reflect a longer period of observation, which in some cases extended over several years. The increase in ${}_{W}\hat{R}_{0.95}$ with the number of workers on the other hand, may point to larger underlying

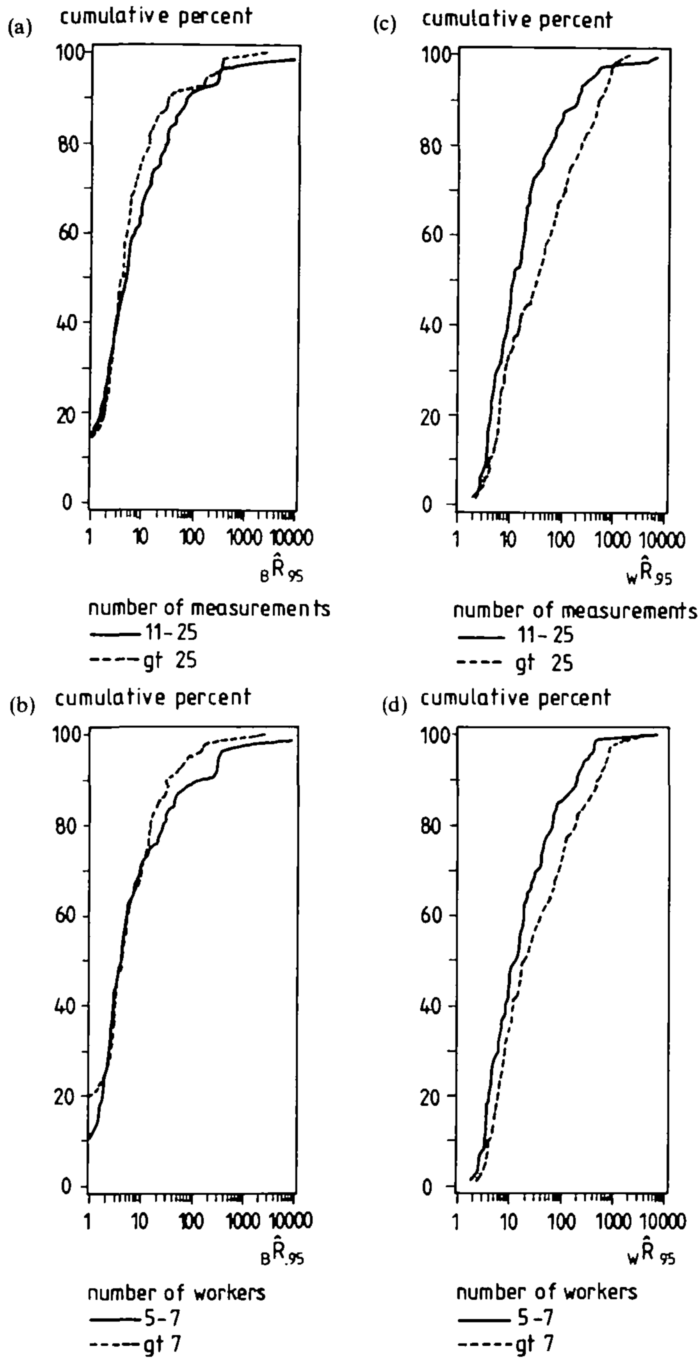

FIG. 2. (a) Cumulative distributions of $_B\hat{R}_{0.95}$ for 92 groups with 11–25 measurements (solid line) and 73 groups with more than 25 measurements (dashed line). (b) Cumulative distributions of $_B\hat{R}_{0.95}$ for 85 groups with five to seven workers (solid line) and 80 groups with more than seven workers (dashed line). (c) Cumulative distributions of $_W\hat{R}_{0.95}$ for 92 groups with 11–25 measurements (solid line) and 73 groups with more than 25 measurements (dashed line). (d) Cumulative distributions of $_W\hat{R}_{0.95}$ for 85 groups with five to seven workers (solid line) and 80 groups with more than seven workers (dashed line).

populations and workplaces. However, given the many combinations of coded variables which comprise the database such conjectures are difficult to confirm.

Influence of type of industry and exposure

The results of subdividing the 165 groups by industry and type of chemical agent are summarized in Table 4. Breaking the 165 groups down by type of chemical agent revealed no differences in the variance components (median $_{W}S_{g}$ 2.05 and 1.97, median $_{B}S_{g}$ 1.34 and 1.44, respectively, for gases and vapours and particulate exposures). The 23 groups with dermal exposures had a median $_{W}S_{g}$ of 2.07 and a median $_{B}S_{g}$ of 1.76. The latter was significantly higher than what was seen for gases and vapours ($P<0.05$, Wilcoxon rank sum test).

TABLE 4. MEDIAN OF TOTAL, WITHIN- AND BETWEEN-WORKER GEOMETRIC STANDARD DEVIATIONS BY TYPE OF INDUSTRY AND TYPE OF CHEMICAL AGENT (NUMBER OF GROUPS IN PARENTHESES)

	Total chemical (96)	Total non-chemical (69)	Total gases–vapours (60)	Chemical gases–vapours (50)	Non-chemical gases–vapours (10)	Total particulate (81)	Chemical particulate (23)	Non-chemical particulate (58)	Total dermal (23)
k	8	6	9.5	10	6	6	6	6.5	7
N	27	22	46	55.5	18	22	18	23.5	19
$_{T}S_{g}$	2.47	2.23	2.29	2.65	1.43	2.34	2.08	2.56	2.56
$_{W}S_{g}$	2.05	1.99	2.05	2.48	1.36	1.97	1.67	2.05	2.07
$_{B}S_{g}$	1.49	1.30	1.34	1.43	1.17	1.44	1.59	1.35	1.76

k, number of workers.
N, number of measurements.
$_{T}S_{g}$, estimated geometric standard deviation of the total distribution.
$_{W}S_{g}$, estimated geometric standard deviation of the within-worker distribution.
$_{B}S_{g}$, estimated geometric standard deviation of the between-worker distribution.

Dividing the groups by type of industry showed a significantly lower $_{B}S_{g}$ ($P<0.05$, Wilcoxon rank sum test) for the non-chemical industry (median $_{B}S_{g}$ 1.30 vs 1.49) but indicated no difference for the $_{W}S_{g}$ (median $_{W}S_{g}$ 2.05 vs 1.99). Subdividing the groups by type of chemical agent and industry, showed significantly higher $_{W}S_{g}$ and $_{B}S_{g}$ distributions for gaseous exposures in the chemical industry ($P<0.001$ and $P<0.01$, respectively). The $_{B}S_{g}$ distribution was also significantly higher for particulate exposure in the chemical industry ($P<0.01$), while the $_{W}S_{g}$ distribution was not significantly different from that observed in the non-chemical industry.

Influence of measurement strategy

The influence of measurement strategy on the distributions of the within- and between-worker variability is depicted in Fig. 3. Groups with non-randomly chosen workers (67 groups) and groups measured on non-randomly chosen days (112 groups) had significantly lower between-worker variability [median $_{B}S_{g}$ 1.33 vs 1.56 ($P<0.01$, Wilcoxon rank sum test) and 1.36 vs 1.75 ($P<0.01$, Wilcoxon rank sum test), respectively]. Groups measured on non-randomly chosen days had, however, significantly higher day-to-day variability than groups measured on randomly chosen days (median $_{W}S_{g}$ 2.12 vs 1.75, $P<0.01$, Wilcoxon rank sum test). The difference for

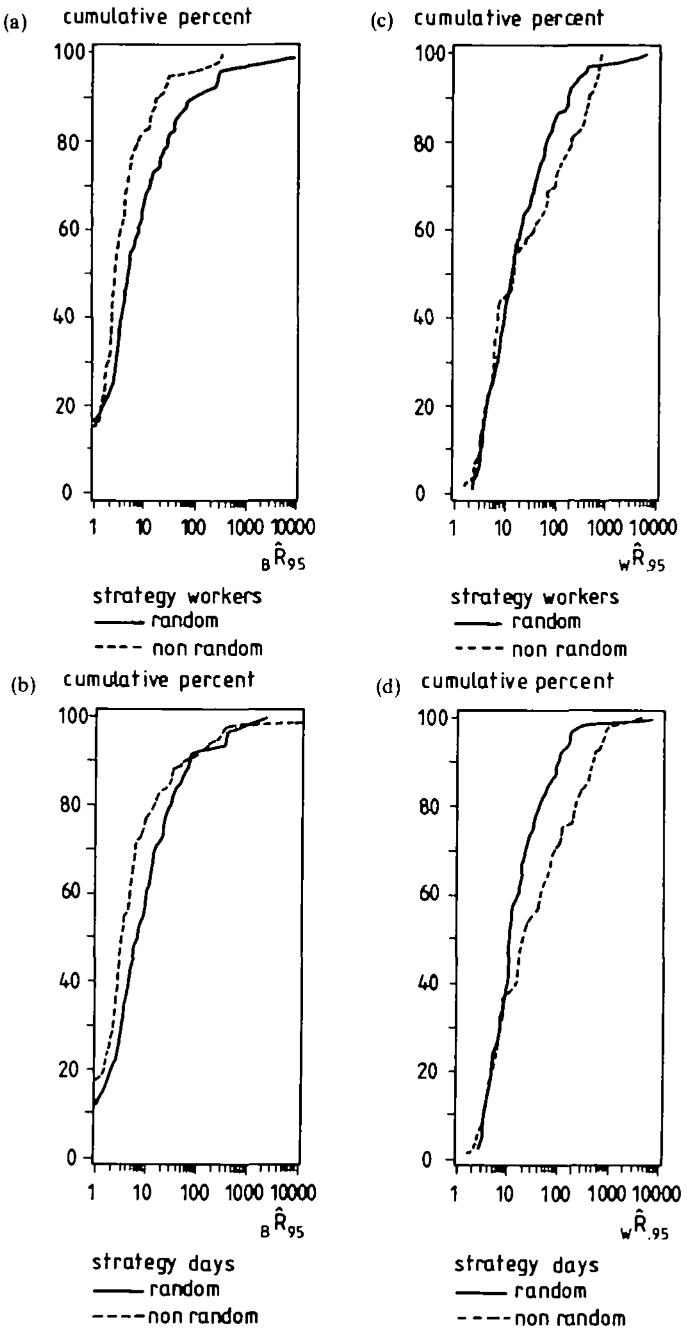

FIG. 3. (a) Cumulative distributions of ${}_{B}\hat{R}_{0.95}$ for 116 groups comprised of randomly chosen workers (solid line) and 67 groups comprised of non-randomly chosen workers (dashed line). (b) Cumulative distributions of ${}_{B}\hat{R}_{0.95}$ for 71 groups measured on randomly chosen days (solid line) and 112 groups measured on non-randomly chosen days (dashed line). (c) Cumulative distributions of ${}_{W}\hat{R}_{0.95}$ for 116 groups comprised of randomly chosen workers (solid line) and 67 groups comprised of non-randomly chosen workers (dashed line). (d) Cumulative distribution of ${}_{W}\hat{R}_{0.95}$ for 71 groups measured on randomly chosen days (solid line) and 112 groups measured on non-randomly chosen days (dashed line).

groups consisting of non-randomly chosen workers was in the same direction, but not statistically significant (median ${}_{W}S_{g}$ 2.02 vs 1.94). No significant differences were seen for the total variability (median ${}_{T}S_{g}$ 2.20 vs 2.32 for non-random and random workers and 2.27 vs 2.26 for non-random and random days).

Influence of environmental and production factors

In Table 5 the results are summarized for the environmental factors, 'indoor–outdoor work' and 'presence of local exhaust ventilation', on the estimated variance components. Groups in which the work was outdoors had significantly higher exposure variability ($P<0.001$), particularly for the within-worker component ($P<0.001$). Similarly, groups working in situations without local exhaust ventilation had significantly higher exposure variability ($P<0.001$), again, primarily due to the within-worker component ($P<0.001$).

TABLE 5. MEDIAN OF TOTAL, WITHIN- AND BETWEEN-WORKER GEOMETRIC STANDARD DEVIATION BY ENVIRONMENTAL FACTORS (NUMBER OF GROUPS IN PARENTHESES)

	Total (87)	Indoors (69)	Outdoors (25)	Local exhaust ventilation (24)	No local exhaust ventilation (63)
k	8	8	15	9	8
N	29	24	74	36	29
${}_{T}S_{g}$	2.28	1.87	3.46***	1.69	2.71***
${}_{W}S_{g}$	2.07	1.73	3.27***	1.57	2.53***
${}_{B}S_{g}$	1.30	1.25	1.43**	1.17	1.39**

k, number of workers.
N, number of measurements.
${}_{T}S_{g}$, estimated geometric standard deviation of the total distribution.
${}_{W}S_{g}$, estimated geometric standard deviation of the within-worker distribution.
${}_{B}S_{g}$, estimated geometric standard deviation of the between-worker distribution.
**$P<0.01$.
***$P<0.001$.

The effect of production variables is given in Table 6. Groups with an intermittent process, or with mobile workers, or with a local source tended to have significantly higher day-to-day variability ($P<0.001$ for 'process' and 'worker mobility', $P<0.01$ for 'type of source') and between-worker variability ($P<0.001$ for 'process', $P<0.05$ for 'worker mobility' and 'type of source'). The differences for the factor 'source mobility' were not statistically significant, but was again in the *a priori* assumed direction.

Multivariate analyses

The results of the multivariate analysis are given in Table 7. A model with environment and process as independent variables explained 41% of the day-to-day variance component. Other process-, environmental- and measurement-strategy-related variables did not contribute significantly. This model predicts the largest within-worker geometric standard deviation for groups of workers working outdoors and with an intermittent process (${}_{W}S_{g}=3.54$). The smallest within-worker component of variability can be expected for groups of workers working indoors and exposed in a continuous process (${}_{W}S_{g}=1.76$).

TABLE 6. MEDIAN OF TOTAL, WITHIN- AND BETWEEN-WORKER GEOMETRIC STANDARD DEVIATION BY PRODUCTION FACTORS (NUMBER OF GROUPS IN PARENTHESES)

	Total (87)	Continuous process (43)	Intermittent process (44)	Mobile worker (54)	Stationary worker (33)	General source (25)	Local source (62)	Mobile source (52)	Stationary source (35)
k	8	7	10	10	7	6	9	13	8
N	29	24	48	41.5	22	24	29	50	24
S_g	2.28	1.70	3.62***	3.07	1.73***	1.76	2.79**	2.50	2.05[ns]
${}_{W}S_g$	2.07	1.60	3.19***	2.72	1.60***	1.68	2.54**	2.37	1.84[ns]
${}_{B}S_g$	1.30	1.23	1.46***	1.41	1.24*	1.23	1.35*	1.34	1.26[ns]

k, number of workers.
N, number of measurements.
${}_{T}S_g$, estimated geometric standard deviation of the total distribution.
${}_{W}S_g$, estimated geometric standard deviation of the within-worker distribution.
${}_{B}S_g$, estimated geometric standard deviation of the between-worker distribution.
*$P<0.05$.
**$P<0.01$.
***$P<0.001$.
[ns]not significant.

TABLE 7. MULTIVARIATE MODELS AND PREDICTIONS OF WITHIN- AND BETWEEN-WORKER VARIABILITY

Within-worker variability Source	DF	SS	MS	*F* value	*P*
Model	2	56.10	28.05	29.39	0.0001
Error	83	79.21	0.95		
R-squared 0.41					

Situation	Estimate (${}_{W}S_g$)	SEE
Indoors and continuous process	1.76	0.15
Indoors and intermittent process	3.13	0.22
Outdoors and intermittent process	3.54	0.20

Between-worker variability Source	DF	SS	MS	*F* value	*P*
Model	1	5.40	5.40	12.92	0.0005
Error	84	35.53	0.42		
R-squared 0.13					

Situation	Estimate (${}_{B}S_g$)	SEE
Continuous process	1.26	0.10
Intermittent process	1.76	0.10

DF, degrees of freedom.
SS, sum of squares.
MS, mean squares.
F value, value of *F* test.
P, significance.
R-squared, explained variability.
SEE, standard error of estimate.

For the between-worker variance component process was the only significant factor in the model. The model predicted that groups of workers exposed in a continuous process had lower between-worker variability (${}_{B}S_{g}=1.26$), while those exposed in an intermittent process had greater between-worker variability (${}_{B}S_{g}=1.76$). However, this model explained only 13% of the variability of the between-worker variance component and the fit was very poor. Thus, it can be concluded that the variables coded in the database only marginally affected the between-worker variance component.

DISCUSSION

The database described in this paper provides a comprehensive overview of within- and between-worker components of occupational exposure to chemical agents throughout industry. The median value of the geometric standard deviation (${}_{T}S_{g}$) of 165 groups based on job title and factory was 2.41 (gases and vapours: ${}_{T}S_{g}=2.29$; particulate matter: ${}_{T}S_{g}=2.34$). LEIDEL *et al.* (1975) reported much lower median values of ${}_{T}S_{g}$ of 1.55 and 1.65 for gases and vapours and particulate matter, respectively. It is unlikely that the variability of occupational exposures has increased dramatically over the last two decades. Rather, we suspect that the small database of LEIDEL *et al.* (1975) was comprised of more homogeneous exposure situations or industries. Our findings are more consistent with those reported by BURINGH and LANTING (1991), where $2.02 \leq$ mean ${}_{W}S_{g} \leq 2.41$ depending on the number of measurements. Our mean value of ${}_{W}S_{g}$ for 165 groups of workers was only slightly higher: 2.47.

In the chemical industry the between-worker variability was significantly higher than in the non-chemical industry (median ${}_{B}S_{g}$ 1.49 vs 1.30). This feature was seen both for aerosols and gases and vapours. The day-to-day variability was more ambiguous with higher variability observed for gases and vapours (median ${}_{W}S_{g}$ 2.48 vs 1.36) than for aerosols (median ${}_{W}S_{g}$ 1.67 vs 2.05). However, since the number of measurements and workers in the groups from the chemical industry was by far the highest for exposure to gases and vapours, the apparent comparison might be confounded.

The notion expressed by ROACH (1991), that exposures tend to vary more with aerosols (dust, fumes and mists) than with gases and vapours, was not corroborated within this database. However, the small number of dermal exposures within the database showed a larger total variability (median ${}_{T}S_{g}=2.56$) suggesting that dermal exposure is more influenced by personal behaviour than is exposure to air contaminants. However, this finding should be interpreted with caution, because the number of groups with measured dermal exposures was very small (23) and all those groups stemmed from a single industry (rubber manufacturing).

The between-worker component of variability was shown to be smaller than the within-worker component (median ${}_{B}S_{g}=1.43$ vs median ${}_{W}S_{g}=2.00$) suggesting that day-to-day differences in exposure to chemical agents were more prominent than differences in mean exposures between workers. The percentage of groups with a ${}_{B}\hat{R}_{0.95} \leq 2$ [uniformly exposed group as defined by RAPPAPORT (1991a)] was higher than presented by RAPPAPORT (1991a) for 31 groups (25 vs 10%). Nevertheless, for almost 30% of the groups within the database the individual mean exposure differed by a factor greater than 10. Apparently, grouping workers by job title and factory does not lead automatically to uniformly exposed groups, as is often assumed (Rappaport *et al.*, 1993).

Sampling on randomly chosen days from randomly chosen workers seems to have an effect on the variance components, particularly for the between-worker variability. Both randomly chosen workers and days resulted in larger between-worker variability, while groups with randomly chosen days had smaller within-worker variability. The data suggest that non-random sampling can lead to problems of interpretation and should be avoided if possible.

It was shown that several factors had an influence on the within- and between-worker variance components of occupational exposure. The number of workers and the number of measurements per group were shown to have distinct effects on the day-to-day variability. A greater number of measured exposures in a group led to a larger estimated within-worker component of variance. Such behaviour would be consistent with the notion that the number of measurements per worker is proportional to the period over which monitoring is conducted. If this period is small (e.g. within 1 week) then it is possible that measurements can be positively autocorrelated since they might reflect only a limited set of conditions, activities and practices which are inherent in the process (Francis *et al.*, 1989, Buringh and Lanting, 1991). This would lead to an underestimation of the variance. However, if the period of observation is large, the variation can also be large, not only because the full range of conditions, etc., is sampled, but also because the underlying distribution of exposures might have changed (Roach, 1991). In either case, the estimated variance should be larger than that obtained from a short period.

The influence of environmental and production factors on the variance components was significant for all but 'stationary–mobile source' and was in all cases in the *a priori* expected direction. The effect was largest for the within-worker component. In the multivariate models the size of the group, type of industry and measurement strategy were not significant. In the case of the within-worker variability two production factors: indoors–outdoors and intermittent–continuous process explained 41% of the variance. Based on the model a two-fold difference in day-to-day variability (${}_{W}S_{y}$) can be predicted between the two extreme situations 'groups working indoors and exposed in a continuous process' and 'groups working outdoors and exposed in an intermittent process'. Although the differences in between-worker variability were also in the *a priori* expected direction (for instance groups with mobile workers were more variable), no suitable multivariate model could be built. A model with 'type of process' as independent variable showed a two-fold difference in between-worker variability (${}_{B}S_{y}$) for 'groups exposed in a continuous process' vs 'groups exposed in an intermittent process'. However, this model explained only 13% of the variance and had a poor fit. Apparently, differences between workers within a group are hardly predictable based on general environmental and production characteristics. More likely, differences between workers are more influenced by factors like work style and the mix of tasks involved (Rappaport *et al.*, 1993).

Given the fact that coding of the environmental and production factors was done retrospectively, we consider the results remarkable. The quality of the codings also depended greatly on details of the actual surveys which were gleaned from reports and interviews with the original investigators. Unfortunately, complete information on all variables was only available for 50% of the groups.

The findings have consequences for measurement strategies both for hazard control and occupational epidemiology. Unfortunately, it seems impossible to predict which groups, based on job title and factory, are more-or-less homogeneously exposed. Therefore, *a priori* assessment of homogeneity is not feasible and measurement strategies must require repeated measurements from the same individuals (RAPPAPORT *et al.*, 1993). Day-to-day variability seems to be more prominent in situations where workers are exposed outdoors in an intermittent process. In order to estimate the group's mean exposure with the same precision 4–5 times more measurements are needed than in a situation were workers work indoors in a continuous process [since the day-to-day exposure variability (${}_{W}S_{y}$) will be 2.2 times as high]. Also, groups with a larger day-to-day variability will show a higher peak-to-mean concentration ratio (considering shift-long average exposure concentrations). This can be very important in the case of exposures resulting in acute effects.

The results of our database show that simple characteristics related to the environment and the process can explain almost half of the within-worker component of variance. Thus, it is now possible, for the first time, to infer the day-to-day fluctuations in exposure based upon information which can be obtained easily. This knowledge can be very useful in the design of strategies for assessing occupational exposure. For example, sample sizes can be selected prior to monitoring of a particular workplace, based upon the nature of the process and the environment.

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REFERENCES

BOS, R. P., KROMHOUT, H., IKINK, H., DE HAAN, W., KOPPEJAN, J. and THEUWS, J. L. G. (1989) Mutagens in urine of non-smoking and smoking workers in an aircraft tyre retreading plant. Skin exposure as a causal factor? *Mutation Res.* **223**, 41–48.

BURINGH, E. and LANTING, R. (1991) Exposure variability in the workplace: Its implications for the assessment of compliance. *Am. ind. Hyg. Ass. J.* **52**, 6–13.

BURINGH, E., VAN DER BELT, R. and VAN DER WAL, J. F. (1990) Dust control measures in Dutch brickworks. *Ann. occup. Hyg.* **34**, 483–497.

CHRISTENSEN, R., PEARSON, L. M. and JOHNSON, W. (1992) Case-deletion diagnostics for mixed models. *Technometrics* **34**, 38–45.

COPE, R., PANACAMO, B., RINEHART, W. E. and TER HAAR, G. L. (1979) Personal monitoring for tetraalkyllead in an alkyllead manufacturing plant. *Am. ind. Hyg. Ass. J.* **40**, 372–379.

FRANCIS, M., SELVIN, S., SPEAR, R. and RAPPAPORT, S. M. (1989) The effect of autocorrelation on the estimation of worker's daily exposures. *Am. ind. Hyg. Ass. J.* **50**, 37–43.

GALVIN, K., SELVIN, S. and SPEAR, R. C. (1990) Variability in protection afforded by half-mask respirators against styrene exposure in the field. *Am. ind. Hyg. Ass. J.* **51**, 625–631.

GEUSKENS, R. B. M., VAN DER KLAAUW, M. M., VAN DER TUIN, J. and VAN HEMMEN, J. J. (1992) Exposure to styrene and health complaints in the Dutch glass-reinforced plastics industry. *Ann. occup. Hyg.* **36**, 47–57.

GOLLER, J. W. and PAIK, N. W. (1985) A comparison of iron oxide fume inside and outside of welding helmets. *Am. ind. Hyg. Ass. J.* **46**, 89–93.

HANSEN, D. J. and WHITEHEAD, L. W. (1988) The influence of task and location on solvent exposures in a printing plant. *Am. ind. Hyg. Ass. J.* **49**, 259–265.

HOLLANDER, A., HEEDERIK, D. and SMID, T. (1988) Longitudinaal longfunktieonderzoek in een scheepsschroevenbedrijf. *T. Soc. Gezondheidsz.* **66**, 253–256 (in Dutch).

KATEMAN, E., HEEDERIK, D., PAL, T. M., SMEETS, M., SMID, T. and SPITTELER, M. (1990) Relationship of airborne microorganisms with the lung function and leucocyte levels of workers with a history of humidifier fever. *Scand. J. Wk Environ. Hlth* **16**, 428–433.

KROMHOUT, H., OOSTENDORP, Y., HEEDERIK, D. and BOLEIJ, J. S. M. (1987) Agreement between qualitative exposure estimates and quantitative exposure measurements. *Am. J. ind. Med.* **12**, 551–562.

LANGE, N. and RYAN, L. (1989) Assessing normality in random effects models. *Ann. Stat.* **17**, 624–642.

LEIDEL, N. A., BUSCH, K. A. and CROUSE, W. E. (1975) *Exposure Measurement Action Level and Occupational Environmental Variability.* NIOSH Technical Information Publ. No. (NIOSH) 76–131. NIOSH, Cincinnati, Ohio.

LINDSTEDT, G., GOTTBERG, I., HOLMGREN, B., JONSSON, T. and KARLSSON, G. (1979) Individual mercury exposure of chloralkali workers and its relation to blood and urinary mercury levels. *Scand. J. Wk Environ. Hlth* **5**, 59–69.

MARQUART, H., VISSCHERS, M., SMID, T. and HEEDERIK, D. (1989) Pulmonary function of welders of zinc-coated mild steel: Cross-sectional analysis and changes over five consecutive work-shifts. *Am. J. ind. Med.* **16**, 289–296.

PETREAS, M. X., RAPPAPORT, S. M., MATERNA, B. L. and REMPEL, D. L. (1992) Mixed exhaled air measurements to assess exposure to tetrachloroethylene in dry cleaners. *J. exp. Assessm. Epidem.*, Suppl. 1, 25–39.

RAPPAPORT, S. M. (1991a) Assessment of long-term exposures to toxic substances in air. *Ann. occup. Hyg.* **35**, 61–121.

RAPPAPORT, S. M. (1991b) Selection of the measures of exposures for epidemiology studies. *Appl. occup. Environ. Hyg.* **6**, 448–457.

RAPPAPORT, S. M., KROMHOUT, H. and SYMANSKI, E. (1993) Variation of exposure between workers in homogeneous exposure groups. *Am. ind. Hyg. Ass. J.* (in press).

RAPPAPORT, S. M., SPEAR, R. C. and SELVIN, S. (1988) The influence of exposure variability on dose–response relationships In *Inhaled Particles VI* (Edited by DODGSON, J., MCCALLUM, R. I., BAILEY, M. R. and FISHER, D. R.), pp. 529–537. Pergamon Press, Oxford.

ROACH, S. A. (1991) Alternative ways of monitoring exposure. In *Exposure Assessment for Epidemiology and Hazard Control* (Edited by RAPPAPORT, S. M. and SMITH, T. J.), pp. 3–20. Lewis Publishers, Chelsea, Michigan.

SMID, T., HEEDERIK, D., MENSINK, G., HOUBA, R. and BOLEIJ, J. S. M. (1992) Exposure to dust, endotoxins, and fungi in the animal feed industry. *Am. ind. Hyg. Ass. J.* **53**, 362–368.

SNEDECOR, G. W. and COCHRAN, W. G. (1980) *Statistical Methods.* Iowa State University Press, Ames, Iowa.

SPEAR, R. C., SELVIN, S., SCHULMAN, J. and FRANCIS, M. (1987) Benzene exposure in the petroleum refining industry. *Appl. ind. Hyg.* **2**, 155–163.

YAGER, J , PARADISIN, W. and RAPPAPORT, S. M. (1993) Sister chromatid exchanges and micronuclei in peripheral lymphocytes of an occupational cohort exposed to styrene. *Mutation Res.* (in press).

WATERS, M., SELVIN, S. and RAPPAPORT, S. M. (1991). A new goodness-of-fit test for the lognormal model applied to occupational exposures. *Am. ind. Hyg. J.* **52**, 493–502.

APPENDIX

TABLE A1. CHARACTERISTICS OF 165 GROUPS (BASED ON JOB TITLE AND FACTORY) WHICH FIT THE RANDOM-EFFECTS MODEL

Group	k	N	$_{W}S_{y}$	$_{W}\hat{R}_{0.95}$	$_{B}S_{y}$	$_{B}\hat{R}_{0.95}$	Chemical agent	Industry
1	5	25	0.305	3.3	0.213	2 3	Perchloroethylene	Dry cleaning
2	5	35	0.661	13.3	0.952	41 8	Inspirable dust	Wool mill
3	5	23	0.326	3.6	0.189	2.1	Inspirable dust	Wool mill
4	12	24	0.610	10 9	0 259	2 8	Inspirable dust	Vehicle manufacture
5	8	16	0 590	10 1	0 287	3.1	Inspirable dust	Vehicle manufacture
6	12	24	0.534	8.1	0.229	2.5	Inspirable iron	Vehicle manufacture
7	7	14	0 345	3.9	0 086	1.4	Inspirable iron	Vehicle manufacture
8	11	22	0 862	29 4	0.000	1.0	Inspirable zinc	Vehicle manufacture
9	8	16	1.155	92.6	0.754	19.2	Inspirable zinc	Vehicle manufacture
10	12	24	0 698	15.5	0.569	9.3	Inspirable copper	Vehicle manufacture
11	8	16	0 384	4.5	0.378	4.4	Inspirable copper	Vehicle manufacture
12	5	22	0.727	17.3	0.000	1.0	Inspirable dust	Vehicle manufacture
13	5	22	0 487	6.7	0.104	1.5	Inspirable zinc	Vehicle manufacture
14	9	36	1.444	287.7	0.000	1.0	Respirable zinc	Brass foundry
15	5	15	1 536	411.3	0.000	1.0	Respirable zinc	Brass foundry
16	6	27	0 687	14.8	0.365	4.2	Inspirable dust	Animal feed production
17	5	18	0.527	7.9	0.676	14 2	Inspirable dust	Animal feed production
18	5	21	0.810	24.0	1.455	300 1	Inspirable dust	Animal feed production
19	6	26	0.989	48.4	0.242	2.6	Inspirable dust	Animal feed production
20	5	18	0.679	14.3	0.852	28.2	Inspirable dust	Animal feed production
21	5	12	1.175	100.3	2.617	28 577	Inspirable dust	Animal feed production
22	9	27	1.206	113 2	1.415	256.7	Inspirable dust	Animal feed production
23	6	26	0.928	38 0	0.496	7.0	Inspirable dust	Animal feed production
24	8	25	1.078	68 5	0 000	1.0	Inspirable dust	Animal feed production
25	6	24	0.764	20 0	0 263	2.8	Inspirable endotoxin	Animal feed production
26	5	17	0.553	8 7	0 556	8 8	Inspirable endotoxin	Animal feed production
27	5	21	1 323	179 0	1 442	284.6	Inspirable endotoxin	Animal feed production
28	6	26	1.329	183.1	0.490	6.8	Inspirable endotoxin	Animal feed production
29	5	18	0.686	14.7	1.187	105.0	Inspirable endotoxin	Animal feed production
30	5	12	1 358	204.9	2.331	9306.4	Inspirable endotoxin	Animal feed production
31	9	27	1 043	59.8	1.260	139.5	Inspirable endotoxin	Animal feed production
32	6	26	1 055	62.6	0.307	3.3	Inspirable endotoxin	Animal feed production
33	8	24	2.099	3743.5	0.405	4 9	Inspirable endotoxin	Animal feed production
34	5	20	0 929	38.2	0.401	4.8	Inspirable dust	Grain mill
35	10	33	1 139	86.8	0.000	1.0	Inspirable dust	Grain mill
36	8	24	0 981	46.7	0.523	7 8	Inspirable dust	Grain mill
37	6	15	0.552	8.7	0.806	23 6	Inspirable dust	Grain mill
38	5	20	1.570	470.1	0.374	4 3	Inspirable endotoxin	Grain mill
39	10	32	1.880	1586.8	0.000	1.0	Inspirable endotoxin	Grain mill
40	8	24	1 324	179.7	0.590	10 1	Inspirable endotoxin	Grain mill
41	5	12	0 895	33.4	0.327	3 6	Inspirable endotoxin	Grain mill
42	7	14	1.060	63.8	1.399	240 5	Inspirable dust	Grain elevator
43	10	20	1.344	194.5	0.952	41.8	Inspirable dust	Grain elevator
44	8	16	1.483	334.4	0.000	1 0	Inspirable dust	Grain elevator
45	9	18	0.793	22 4	1.099	74.2	Inspirable dust	Grain elevator
46	8	24	0.704	15.8	0.277	3 0	Inspirable dust	Tobacco products
47	5	15	0.710	16 1	0.422	5 2	Inspirable dust	Tobacco products
48	10	29	0.468	6 3	0.295	3 2	Inspirable dust	Tobacco products
49	7	21	0.371	4.3	0.255	2.7	Inspirable dust	Tobacco products
50	8	24	0.432	5.4	0.000	1.0	Inspirable nicotine	Tobacco products
51	5	15	0.349	3 9	0.224	2.4	Inspirable nicotine	Tobacco products
52	10	28	0.348	3 9	0.102	1 5	Inspirable nicotine	Tobacco products
53	7	21	0.356	4.0	0.000	1 0	Inspirable nicotine	Tobacco products
54	6	17	0.927	37.9	0.979	46.4	Inspirable dust	Rubber manufacture
55	18	36	0.829	25 8	0 369	4.3	Inspirable dust	Rubber manufacture
56	5	14	0.251	2.7	0.180	2.0	Inspirable dust	Rubber manufacture
57	6	18	0.736	17.9	0.768	20.3	Inspirable dust	Rubber manufacture
58	8	22	0.547	8.5	0.465	6.2	Inspirable dust	Rubber manufacture
59	6	18	0.368	4.2	0.268	2.9	Inspirable dust	Rubber manufacture
60	5	13	0.327	3 6	0.155	1.8	Inspirable dust	Rubber manufacture
61	5	11	0.467	6.2	0.767	20.2	Inspirable dust	Rubber manufacture
62	5	14	0.482	6 6	0.653	13.0	Inspirable dust	Rubber manufacture
63	5	12	0.303	3.3	0.855	28.6	Inspirable dust	Rubber manufacture

TABLE A1—*continued*

Group	k	N	$_wS_y$	$_w\hat{R}_{0.95}$	$_BS_y$	$_B\hat{R}_{0.95}$	Chemical agent	Industry
64	6	18	0.473	6.4	0.335	3.7	Inspirable dust	Rubber manufacture
65	6	13	0 403	4.9	0.293	3.2	Inspirable dust	Rubber manufacture
66	7	21	0.521	7.7	0.428	5.4	Inspirable dust	Rubber manufacture
67	9	25	0.337	3.7	1.019	54 2	Inspirable dust	Rubber manufacture
68	7	21	0.572	9.4	0.249	2.7	Inspirable dust	Rubber retreading
69	5	14	0.739	18.1	1.067	65.5	Inspirable dust	Rubber retreading
70	6	13	0.569	9.3	0.483	6 6	Inspirable dust	Rubber manufacture
71	12	32	0.516	7.6	1.939	1999.3	Inspirable dust	Rubber manufacture
72	11	28	0.397	4 7	0.000	1.0	Inspirable dust	Rubber manufacture
73	6	16	0.763	19.9	1.716	833.4	Inspirable dust	Rubber manufacture
74	7	20	1.407	248.6	0.000	1.0	Cyclohexane soluble dermal	Rubber manufacture
75	7	19	1.056	62.9	0.616	11.2	Cyclohexane soluble dermal	Rubber manufacture
76	8	21	0.781	21.4	0.671	13.9	Cyclohexane soluble dermal	Rubber manufacture
77	5	13	1.097	73.7	0 136	1.7	Cyclohexane soluble dermal	Rubber manufacture
78	6	18	1.294	159.8	0 948	41.1	Cyclohexane soluble dermal	Rubber manufacture
79	8	22	0.419	5.2	0.349	3.9	Cyclohexane soluble dermal	Rubber manufacture
80	6	16	0.296	3.2	0.024	1.1	Cyclohexane soluble dermal	Rubber manufacture
81	7	20	0 948	41.1	0 412	5.0	Cyclohexane soluble dermal	Rubber manufacture
82	6	13	2.239	6473.0	0.306	3 3	Cyclohexane soluble dermal	Rubber manufacture
83	5	14	1.014	53 2	1.442	285.1	Cyclohexane soluble dermal	Rubber manufacture
84	5	16	0.560	9 0	0.522	7.7	Cyclohexane soluble dermal	Rubber manufacture
85	6	14	0.321	3 5	0.874	30.8	Cyclohexane soluble dermal	Rubber manufacture
86	9	25	0.701	15.6	0.653	12.9	Cyclohexane soluble dermal	Rubber manufacture
87	12	25	0.606	10.8	0.000	1.0	Cyclohexane soluble dermal	Rubber manufacture
88	8	23	1.134	85.4	1 066	65.2	Cyclohexane soluble dermal	Rubber manufacture
89	10	27	0.898	33.7	0 847	27.7	Cyclohexane soluble dermal	Rubber manufacture
90	6	14	0 729	17.5	0.563	9.1	Cyclohexane soluble dermal	Rubber manufacture
91	9	27	0.592	10.2	0.606	10.7	Cyclohexane soluble dermal	Rubber retreading
92	5	14	0.306	3 3	0.110	1.5	Cyclohexane soluble dermal	Rubber retreading
93	7	19	0.567	9.2	0.795	22.5	Cyclohexane soluble dermal	Rubber manufacture
94	15	40	0.554	8 8	0.545	8.5	Cyclohexane soluble dermal	Rubber manufacture
95	15	39	0.611	11 0	0.643	12.4	Cyclohexane soluble dermal	Rubber manufacture
96	5	14	0.809	23.8	0.000	1.0	Cyclohexane soluble dermal	Rubber manufacture
97	12	77	0.409	5.0	0.411	5.0	Diphenyl	Synthetic yarn manufacture
98	5	28	0.236	2.5	0.249	2.7	Diphenyl	Synthetic yarn manufacture
99	12	77	0 436	5.5	0 432	5.4	Diphenyl ether	Synthetic yarn manufacture
100	5	29	0.298	3.2	0.193	2.1	Diphenyl ether	Synthetic yarn manufacture
101	11	48	0.946	40.8	0.678	14.3	Inspirable dust	Pesticides formulation
102	13	57	0.489	6.8	0.309	3.4	Inspirable dust	Pesticides formulation
103	5	91	0.961	43.2	0 000	1.0	Nitrogen dioxide	Fertilizer manufacture
104	10	28	1.562	455.6	0.000	1 0	Styrene	Reinforced plastics
105	8	23	0.617	11 2	0.859	29.0	Styrene	Reinforced plastics
106	8	32	0.462	6 1	0.357	4.0	Styrene	Reinforced plastics
107	7	18	0.704	15.8	0.000	1.0	Styrene	Reinforced plastics
108	8	24	0.507	7.3	0.000	1.0	Styrene	Reinforced plastics
109	10	30	0 204	2.2	0 269	2.9	Styrene	Reinforced plastics
110	6	18	0.208	2.3	0 392	4.6	Styrene	Reinforced plastics
111	8	24	0.267	2.8	0.422	5.2	Styrene	Reinforced plastics
112	6	29	0.457	6.0	0.218	2 4	Welding fume	Locomotive manufacture
113	6	29	0.459	6.0	0.147	1 8	Welding fume	Locomotive manufacture
114	6	29	0.521	7.7	0.206	2.2	Welding fume	Locomotive manufacture
115	6	29	0.446	5.8	0.211	2.3	Welding fume	Locomotive manufacture
116	10	27	0.440	5.6	0.427	5.3	Diphenyl ether	Synthetic yarn manufacture
117	6	16	0 377	4.4	0.354	4.0	Diphenyl ether	Synthetic yarn manufacture
118	5	14	0.584	9.9	0.557	8.9	Diphenyl ether	Synthetic yarn manufacture
119	9	21	0.309	3.4	0.000	1.0	Ethanal	Synthetic yarn manufacture
120	7	21	0.146	1.8	0.148	1.8	Solvent vapours	Printing plant
121	14	68	0.470	6 3	0.471	6.3	Styrene	Reinforced plastics
122	6	33	1.095	73.0	1.469	316.3	Styrene	Reinforced plastics
123	8	48	1.284	153.7	0.734	17.7	Styrene	Reinforced plastics
124	6	27	1.251	134.7	1.488	341.7	Styrene	Reinforced plastics
125	53	382	1.022	54.9	0.530	8.0	Toluene	Petroleum refining
126	5	39	0.845	27.4	0.353	4.0	Toluene	Petroleum refining
127	6	176	0.848	27.8	0.393	4.7	Tetraalkyl lead	Alkyl lead manufacture
128	6	177	0.614	11.1	0.153	1.8	Inorganic lead	Alkyl lead manufacture
129	38	201	1.184	103.8	0.264	2.8	Benzene	Petroleum refining

TABLE A1—*continued*

Group	k	N	$_{W}S_{y}$	$_{W}\hat{R}_{0.95}$	$_{B}S_{y}$	$_{B}\hat{R}_{0.95}$	Chemical agent	Industry
130	17	89	0.683	14.5	0.193	2.1	Benzene	Petroleum refining
131	18	57	0.693	15.1	0.152	1.8	Benzene	Petroleum refining
132	38	164	1.208	113.8	0 285	3.1	Benzene	Petroleum refining
133	17	74	1.556	445.3	0.557	8.9	Benzene	Petroleum refining
134	16	50	0.733	17 7	0 222	2.4	Benzene	Petroleum refining
135	5	44	1.492	346.9	0.385	4.5	Benzene	Petroleum refining
136	10	54	1.620	571 7	0.824	25.3	Benzene	Petroleum refining
137	8	68	1.671	699.5	0.299	3.2	Benzene	Petroleum refining
138	22	145	1 705	799.0	0.715	16.5	Benzene	Petroleum refining
139	17	118	1.072	66.7	0.243	2.6	Benzene	Petroleum refining
140	18	90	1.348	197.2	0.134	1.7	Benzene	Petroleum refining
141	25	105	0.820	24.9	0.404	4.9	Benzene	Petroleum refining
142	14	87	0.936	39.3	0.355	4 0	Benzene	Petroleum refining
143	13	73	1.183	103 1	0.249	2.7	Benzene	Petroleum refining
144	15	87	1.092	72.2	0.360	4.1	Benzene	Petroleum refining
145	15	167	1.522	390 0	0.649	12.8	Benzene	Petroleum refining
146	14	38	1.699	781.8	1.278	149.6	Benzene	Petroleum refining
147	13	50	1 403	244.8	0 642	12.4	Benzene	Petroleum refining
148	15	36	0 344	3.9	0 000	1.0	Sulphur dioxide	Aluminum reduction
149	16	38	0 539	8.3	0.000	1.0	Total dust	Aluminum reduction
150	14	34	0.347	3.9	0.089	1 4	Total fluoride	Aluminum reduction
151	14	34	0.385	4 5	0.000	1.0	Fluoride dust	Aluminum reduction
152	15	36	0.293	3 2	0.205	2.2	Hydrogen fluoride	Aluminum reduction
153	26	79	0.880	31.5	0.000	1.0	Formaldehyde	Resin manufacture
154	8	24	0 668	13.7	0.259	2.8	Formaldehyde	Resin manufacture
155	6	54	1 390	232.6	0 000	1.0	Organic vapour	Pesticide manufacture
156	5	1139	1 525	394.3	0.435	5.5	Organic vapour	Pesticide manufacture
157	16	5076	1.723	856.3	0.341	3.8	Organic vapour	Pesticide manufacture
158	62	1162	1.638	615.4	0.857	28.8	Organic vapour	Pesticide manufacture
159	16	592	0.517	7.6	0.232	2.5	Inorganic mercury	Chloralkali production
160	6	18	0.367	4.2	0.091	1.4	Benzene	Spray painting
161	6	18	0 308	3.3	0.212	2.3	Benzene	Spray painting
162	6	18	0 245	2.6	0.165	1.9	Toluene	Spray painting
163	6	18	0.694	15.2	0.000	1.0	Toluene	Spray painting
164	6	18	0.363	4.1	0.060	1.3	Xylene	Spray painting
165	6	18	0.241	2.6	0.270	2.9	Xylene	Spray painting

k, number of workers in a group.
N, number of measurements in a group.
$_{W}S_{y}$, estimated standard deviation of within-worker distribution of log-transformed exposures.
$_{W}\hat{R}_{0.95}$, ratio of the 97.5th and 2.5th percentiles of the within-worker distribution.
$_{B}S_{y}$, estimated standard deviation of between-worker distribution of log-transformed exposures.
$_{B}\hat{R}_{0.95}$, ratio of the 97.5th and 2.5th percentiles of the between-worker distribution.