CHAPTER 4:
EXPOSURE TO BENZENE IN FUEL DISTRIBUTION INSTALLATIONS: MONITORING AND PREVENTION

C. Peretz, P. Froom, A. Pardo, A. Goren

Arch Environ Health. 2000 ;55(6):439-46

ABSTRACT

An association between airborne benzene exposure and task and timing factors was examined, applying a mixed effects model on a cohort of 258 workers randomly chosen, in 7 fuel distribution facilities. During 8 years, 692 repeated personal measurements were performed. Filler-task, warm month, Tuesday, credit-day and period (1992-1996) were significantly associated with higher exposure to benzene. After controlling for the period effect, task-type was found to highly affect the between worker variance and thus, two homogeneous exposure groups - fillers and non-fillers are adequate for exposure grouping strategy. The timing factors were found to affect the high within worker variance (>2 than between worker variance) after controlling for the task and period effects. To better represent long-term exposure, the sampling strategy should be stratified by warm/non warm months and measurement days should be selected randomly.

INTRODUCTION

Long-term low level exposures to benzene (less than 10 ppm) have been recently found to be probably associated with acute myeloid leukemia.[1] The major occupational sources for benzene exposure, -through the inhalation of gasoline vapors-, in the fuel supply industry ,are oil refineries, distribution facilities and service stations. Exposure levels of benzene among attendants in service stations are generally lower than the existing Threshold Limit Value (TLV), 1 ppm, and are primarily affected by the type of fuel, the work practice, the work load and weather conditions.[2-6] However, the time weighted average exposure levels reported for distribution facilities and refineries are higher, 0.003-8.9 ppm.[7-8] They are probably affected by additional factors, especially the task and the filling method.[5,7-12] Assessing long term exposure in occupational groups is essential for exposure-response evaluation.[13-15] Assessing the determinants of exposure is essential for hazard control and for effective use of control measures.[13,16-18] However, due to study limitations, the exposure assessment in those studies was not satisfactory.[1,10] In many situations, chronic exposures have been inferred on the basis of a one-time exposure survey or successive surveys carried out over a short period.[19] Since exposure varies within the same worker over time, [13,19-24] even to a very high degree, [5,19,22] this practice may cause bias since a single survey as well as successive surveys - which may result in autocorrelated exposures[25] - may not represent long term exposure. For a valid exposure assessment, monitoring designs should be based on repeated measurements within the same worker.[4,19,23]

Occupational labor inspection regulations for benzene in Israel stipulate that: (i) Airborne benzene monitoring should be carried out four times a year (every 3 months) in fuel distribution facilities, and the exposure results should be kept for 20 years (ii) A Threshold Limit Value (TLV-TWA) of 0.6 ppm and an Action Level (AL) of 0.3 ppm were established (iii) Biological monitoring and medical surveillance along time. However, only a few studies regarding exposure assessment to chemicals at workplaces, based on multiple non successive repeated measurements over time, have been published should be conducted every 6 months among workers exposed above the Action Level and among all workers in the production of benzene or in filling tankers or storage tanks.

The existence of a systematic and accessible long-term exposure data-base for all fuel distribution facilities in Israel, enables the investigation of benzene monitoring for both exposure assessment and exposure determinants, in this industry. Thus, the specific aims of the present study were to evaluate the association between work task and exposure and between timing factors - day, month, year and exposure. Moreover, since it is known that exposure in occupational groups varies between and within-workers, these variance components were estimated in different conditions.

METHODS

Study subjects

The study cohort included 258 workers from 7 fuel distribution facilities in Israel, whose environmental monitoring was carried out systematically during 8 years (1989-1996). In each monitoring survey the workers selected to represent the main processes in each facility. The major tasks were: fuel-filling (top loading), maintenance, gate-guarding, workshop activities, and laboratory work. All except one were men and besides two laboratory, the workers were all blue-color workers. The number of fillers in each facility varied between 3-33 and comprised 55% of the study cohort.

Environmental monitoring

In each installation 2-4 hygiene surveys were performed each year. Altogether, 18-32 surveys were performed at each facility during the whole period, giving a total of 151 surveys. The sampling strategy employed was monitoring a representative number of workers in all work-areas with potential exposure. The sampling scheme varied from one survey to another depending on different selection of workers by different hygienists who performed the surveys. The majority of the samples were personal breathing zone samples in which air was drawn through a commercial charcoal tube (SKC226-01). Benzene analysis was carried out by gas chromatography. In addition to internal quality controls, validation was verified by participation in external quality assurance programs of

Proficiency Analytical Testing (PAT) and Workplace Analytical Scheme for Proficiency (WASP).

Repeated measurements

Results of 692 full shift personal measurements, time weighted average, were included in the study. Of these, 64% were performed on fuel-fillers. The repetitions varied between 1-12 measurements per worker along the 8 years. Fifty five percent of the workers had two or more repeated measurements; 16% had over 5 repetitions.

Data source

Data were obtained from the occupational hygiene unit of the Institute for Occupational Health of Tel Aviv University. Each observation included the following variables: exposure concentration, date (day, month, year), measuring type (personal/fixed points), department and workstation identification - usually including subject name. Due to non-uniformity in the department name and workstation identification even within the same facility, a rearrangement was done for these two variables with a suitable coding.

Statistical analysis

Univariate analysis: descriptive statistics, such as geometric means and standard deviations, maximum likelihood arithmetic means and proportions, were used to describe benzene exposure by different characteristics. Multivariate analysis: to associate between exposure (dependent variable) and its determinants (independent variables) a multiple model, the mixed effects model for unbalanced data was used.[26-29] The dependent variable was the log-transformed values of benzene concentrations since these concentrations were assumed to have a log-normal distribution.[15,19-22] The five dichotomous independent variables were: work-task (filler, non-filler), month (warm, non-warm), day of the week (Tuesday, other), credit-day (yes, no) and period (1989-1992, 1993-1996). [*]

[*] Credit day is an account day and the day after it:1,2,10,11,15,16,20,21,30,31 of each month. The days on which the gasoline stations prefer to receive supply due to financial considerations

Details regarding the model are presented in the Appendix. To investigate variance components, three hierarchical mixed effects models were applied. The first included only the background exposure (=the intercept), while the second included the task and period effects and the background exposure. The third included all 5 exposure effects, the independent variables and the background exposure.

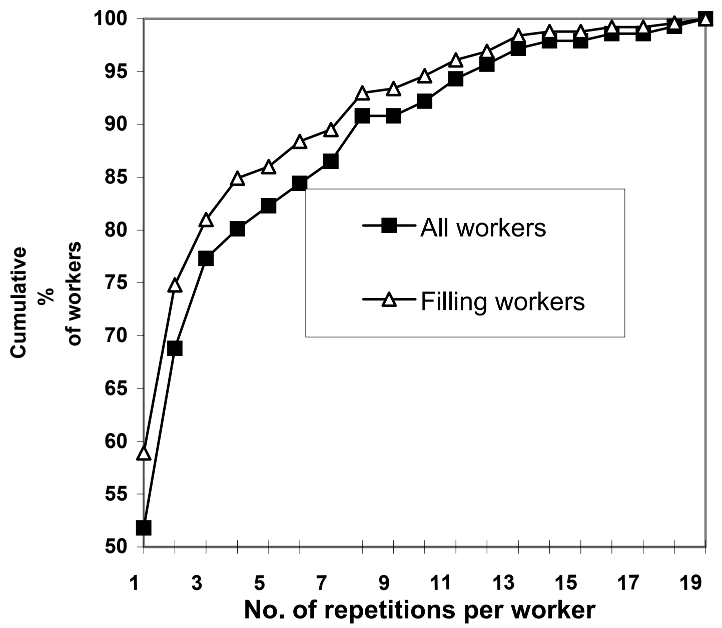
The application of the mixed effects models was carried out using PROC MIXED from the SAS System Software,[30] and the estimation of the variance components was done by using the Restricted Maximum Likelihood (REML) method.

RESULTS

Data description

The accumulated percentage of workers by number of repeated measurements per worker is shown in Fig 4.1, both for the fillers and for the whole group.

Fig 4.1. Distribution of workers by number of repeated measurements per worker (n=692)



Twenty percent of the workers had more than 3 repeated measurements and among the fillers twenty percent had more than 4 repeated measurements. The analysis is based on 692 measurements performed on 258 workers, along 8 years of follow-up. Table 4.1 presents univariate statistics of benzene distribution by specific characteristics (exposure determinants), assuming independence between repeated measurements within a worker.

Table 4.1 Benzene exposure (ppm) by specific characteristic among gasoline distribution workers

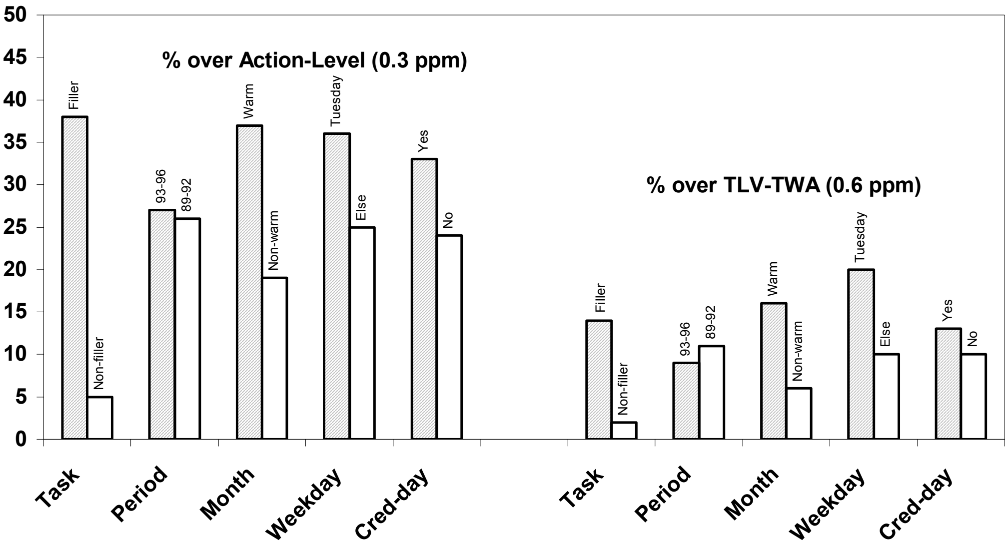
Characteristic		k	n	AM	GM	GSD	P-value
Task	Filler	141	445	.38	.18	3.35	
	Non-filler	117	247	.07	.03	3.25	<.0001
Month	Warm[a]	196	411	.43	.14	4.44	
	Non-warm	144	281	.20	.08	3.97	<.0001
Week-day	Tuesday	77	105	.36	.12	4.31	
	Other	228	687	.27	.10	4.22	BS(.1021)
Credit-day	Yes[b]	121	202	.35	.13	4.14	
	No	205	490	.26	.09	4.26	.0048
Period	1989-1992	110	268	.29	.10	4.39	
	1993-1996	182	424	.28	.10	4.18	NS
Total		258	692	.29	.10	4.26	

NOTES: k = no. of workers; n = no. of measurements;
AM = Maximum likelihood Arithmetic Mean; GM = Geometric Mean;
GSD = Geometric Standard Deviation; BS =.05<P-value<=.10; NS = P-value>.10
[a] Warm months: Jun., Jul., Aug., Sept.
[b] Days of the month when it is financially advantageous to receive supply

Significant higher geometric mean exposures can be observed amongst fillers, on warm months and on credit-days. There was a borderline significant difference in the geometric mean exposure on Tuesdays in comparison to all other days. A non-significant difference between the geometric mean exposures in the 2 periods, 1989-1992 and 1993-1996 could be demonstrated.

Compliance may be regarded with respect to the percentage of results exceeding exposure standards. The percentage of results exceeding the Israeli TLV-TWA and AL, by specific characteristics, are presented in Fig 4.2.

Fig 4.2. Percentage of measurements (n=692) that exceeded standards, by specific characteristics



A difference in the level of overexposure, in relation to the TLV-TWA, between the categories of 4 characteristics (task, month, week-day, credit-day) can be seen. These differences are even larger regarding exposure over the AL. There is almost no difference in percentage of overexposure between the 2 periods

Exposure factors relating to benzene levels in the air

In Table 4.2, the modeling of exposure determinants by the multiple mixed effects model is presented. As can be seen from this table, all the 5 effects were significantly associated with exposure. The coefficients of the model represent the contribution of the factors to the mean exposure expressed as log-transformed benzene concentrations, when a value of 1 was assigned to task (meaning fillers), month (meaning a warm month), week-day (meaning Tuesday), credit-day (meaning a credit day), period (meaning 1989-1992). The background geometric mean exposure was found to be 0.03 ppm (Table 4.2, intercept).

Table 4.2 Factors affecting benzene exposure (log-transformed benzene concentrations in ppm) according to a mixed effects model (based on 258 workers and 692 measurements)

Factor	Coefficient	(SE)	P-value	Exponent of Coefficient
Intercept	-3.62	(.10)	.0001	0.03
Task	1.71	(.11)	.0001	5.52
Month	0.49	(.09)	.0001	1.63
Week-day	0.19	(.09)	.0492	1.21
Credit-day	0.24	(.10)	.0148	1.27
Period	0.27	(.10)	.0048	1.31

NOTE: SE=Standard Error

In order to calculate the estimated geometric mean exposure in different conditions, the exponent of coefficients (= factors) should be multiplied by 0.03 and by each other. Task was found to be the most important factor associated with exposure. Geometric mean exposure to benzene was 5.5 times higher among fillers than among non-fillers. It is noteworthy that the results for fillers are related to top loading. Each of the other factors - month, week-day and credit-day, significantly increased the geometric mean exposure by a factor less than two. The simultaneous existence of all of the factors, increased the exposure 2.5 fold (1.63*1.21*1.27).

In addition, a significant period effect was found since the geometric mean exposure in 1993-1996 was 1.3 times higher than that in 1989-1992. Thus, the period effect should be controlled for the association between exposure and task and date determinants. It should be noted that in the univariate analysis (Table 4.1), the p-value of the period characteristic was non-significant, while in the multiple analysis (Table 4.2) it was found significant.

When the mean exposure is above exposure standards, such as TLV-TWA and AL, remedial action should be taken and control devices should be applied to reduce exposure. Table 4.3 shows the estimated geometric mean (GM) exposures of fillers and non-fillers in different conditions controlled for period effect.

Table 4.3 Estimated Geometric Mean (GM) exposure to benzene (ppm) according to the mixed effects model in 8 out of 32 possible conditions (based on 258 workers and 692 measurements)

Period	Task	Condition	GM Exposure
1993-1996	Filler	Warm month, Tuesday, credit day	0.41
		Warm month, not Tuesday, non-credit day	0.28
		Not warm month, not Tuesday, non-credit day	0.17
	Non-filler	Warm month, Tuesday, credit day	0.07
1989-1992	Filler	Warm month, Tuesday, credit day	0.31
		Warm month, not Tuesday, non-credit day	0.21
		Not warm month, not Tuesday, non-credit day	0.13
	Non-filler	Warm month, Tuesday, credit-day	0.05

The highest 3 GM exposures of fillers were 0.41 ppm, 0.31 ppm and 0.28 ppm. With an action level of 0.3 ppm in Israel, these conditions indicate potential hazardous situations that should be controlled in order to reduce exposure. In contrast, even in the most extreme conditions of high potential exposure, non-fillers were subject to very low mean exposures, of 0.07 ppm and 0.05 ppm, in the different periods.

Variance components of benzene concentrations

In Table 4.4, the estimators of variance components of the benzene concentrations are shown in geometric standard deviations. The geometric standard deviations between workers and within workers, in the 8 years of follow up, are presented in 3 hierarchical mixed effects models.

Table 4.4 Within- and between-worker variability in 3 models relating various factors to exposure (based on 258 workers and 692 measurements)

	MODEL 1 (factors=none)		MODEL 2 (factors=task, period)		MODEL 3 (factors=task, month, week-day, credit day, period)	
Component	Estimate	P-value	Estimate	P-value	Estimate	P-value
GSD- b	2.34	.0001	1.34	.0729	1.37	.0305
GSD- w	3.26	.0001	3.21	.0001	3.07	.0001

NOTES: GSD-b/w=Geometric Standard Deviation, between/within-worker;
P-value, estimate not equal one

The first model, a one way random effects model, included only the background exposure. The second model included in addition the task and period factors, and the third model included all the 5 factors affecting the exposure in addition to the background exposure. In all the models the geometric standard deviation components were at least borderline significantly different from 1 (namely the variances were different from zero).

In Models 2 and 3, the GSD-w were found to be 3.21 and 3.07 respectively, more than twice higher then the GSD-b which were 1.34 and 1.37 respectively. The work-task was found to be the major predictor of exposure and was responsible for a 43% reduction of the GSD-b ((2.34-1.34)/1.34*100) based on comparing a model without exposure determinants (Model 1) to a model including task and controlling for the period effect (Model 2). However the month, credit-day and day of the week were responsible for a reduction of 6% of the GSD-w ((3.26-3.07)/3.26*100), controlling for task and period when comparing model 3 to model 1. Since the variance components may be different in the different task groups[13,22,33] the variance components were estimated separately for fillers and non-fillers (Table 4.5). The estimations, controlled for other exposure-factors, seemed to be of the same order of magnitude in both task groups.

Table 4.5 Within- and between-worker variability in 2 task-group; controlling for month, week-day, credit-day

	Task	
	Fillers	Non-fillers
No. of workers	141	117
No. of measurements	445	247
GSD- b	1.39	1.25
GSD- w	3.07	3.13

NOTES: GSD-b/w= Geometric Standard Deviation, between/within-worker

DISCUSSION

The aim of this comprehensive follow-up study was to assess exposure to benzene in the fuel distribution industry in Israel and to investigate exposure determinants. The study included environmental monitoring data gathered over eight years of follow-up. The analysis was based on accumulated data compiled for administrative purposes on an ongoing basis. Even though exposure registries could be a useful tool in public health response to occupational exposure, such evaluations are rarely done.

Since this is a historical-prospective study, the exposure determinants examined were limited to those mentioned in the data-source. The study might be slightly biased due to non uniform schemes of workers monitoring. However, there is no reason to assume any specific bias and consequently the study results may be generalized.

In a mixed effects model for an unbalanced repeated measurements design, five determinants, task and four timing factors (month, week-day, credit-day, period) were tested for their effects on benzene exposure. A strong task-type effect was found. Fuel-filling workers, on average, experienced exposure levels 5 times higher than all other types of workers. Controlling for the four timing determinants, the predicted average exposure of the fillers was 0.41 ppm in their presence (namely on warm months, Tuesdays, credit-days, second period) as opposed to 0.13 ppm in their absence. Exposure standards aim to prevent health impairment of workers. Exposure of 0.41 ppm is higher than the action level of 0.3 ppm, thus, a sincere effort should be made in all the facilities to reduce fillers exposure.

An averaged benzene concentration of 0.17 ppm (=0.55 mg/m^3) was found in an Italian study regarding 111 filling station attendants in Rome, which were monitored 6.3 times (on average) during one year.[4] The exposure of the non-fillers found in our study is of the same order of magnitude as that of benzene attendants .

In this study warm months, and to a lesser extent, credit-days, Tuesdays and the later period were associated with increased exposures to benzene. Warm months in Israel (June-September) are characterized by high temperatures, on average 24°c ±0.5 (opposed to 18°c ±3.5 during the rest of the year), which cause higher fuel evaporation and consequently higher exposures. The average exposure level obtained on warm months was 1.6 times higher than on non-warm months. Credit-days indicate higher activity, since it is financially advantageous for the gasoline stations to receive supply on the account day and the following day. Exposure on credit-days was 1.3 times higher than on non credit-days. An attempt was made to associate the day of the week and the level of exposure, controlling for all the other exposure determinants. A higher average exposure was found on Tuesdays, indicating a work peak, compared to the beginning and the end of the week. According to a subjective estimate of workers in the facilities, the work-load has been uniformly distributed during the week, except for the higher work load on credit-days. Since we did find an effect of the day of the week this effect should be further investigated.

During the 8 years of the follow up, there were no changes in the sampling and analysis methods or in work processes (including job-tasks and equipment) . The percent of benzene in the fuel ranges from 1.5%-2.5%, the variation being due to differences between refineries and to market demands. However, it is known that measurements taken over periods longer than 5 years appear to exhibit systematic changes in exposure results. [31] In order to control for a period effect, the 8 years of the follow up were divided into two periods, of four years each. A period effect was included in the multiple mixed effects model and indeed was found to be significant. The average exposure of the period 1993-1996 was 1.3 times higher than that of the period 1989-1992. This may be due to changes in work load. Hence, the period effect should be controlled for in the investigation of the exposure and its determinants over a long period of follow-up.

In order to reduce the exposure to benzene, it is essential that hygienists, occupational physicians, employers and workers understand the main factors contributing to higher exposure. Extreme conditions should therefore be better controlled in order to avoid risky situations. Such information can also assist hygienists in planning a representative environmental sampling strategy and thus better assess occupational exposure for both hazard control and epidemiological studies - of exposure-response relationships. Based on our findings, warm months and credit-days should be considered as part of the sampling strategy. Today the sampling surveys are performed on fixed months in each facility and thus may not represent higher exposures on warm months. This procedure should be changed to a stratified one by warm and non-warm months. In addition, selecting measurement days at random should maximize the likelihood that they are representing different work load conditions.

Modeling exposure and its determinants has always been performed by regression models.[16] In repeated measurements designs, this means ignoring the dependence between the measurements , a procedure which may entail biased models for assessing exposure. The mixed effects model used in this study enables handling unbalanced repeated measurements and modeling exposure in a more efficient way.

Estimating exposure variance components between and within workers in homogeneous exposure groups is essential for exposure assessment.[13,15,22,32-34] Several investigators have ignored the contribution of exposure determinants and used a one way analysis of variance model to estimate variance components in task groups, thus limiting the possibility of understanding the factors affecting within and between worker variance.[22,23,33] In a study regarding benzene exposure in petroleum refining, 19 task groups were defined and had varying GSD-b and GSD-w values (1.0-9.29). However, the period effect was not controlled for as has recently been suggested by Symanski et al.,[31] nor were other timing effects controlled.

Since in this study, task was found to highly influence the between worker variance, two homogeneous exposure groups- fillers and non-fillers were found to be adequate for exposure grouping strategy in this industry. The geometric standard deviation within-workers was found to be more than twice higher than that between workers, after controlling for the task and time effects, meaning a wide range of exposure levels for each worker during a time period. Control of factors which affect the within-worker variance of exposure such as: month, credit-day and day of the week may assist in reducing exposure levels. Other work characteristics such as worker-mobility, source mobility, ventilation, personal hygiene etc. may affect the within-variance exposure.[19,22]

In conclusion, the mixed effects model used in this study enables a better assessment of occupational exposure and a better assessment of the relative contribution of exposure determinants. Consequently, more effective prevention of hazardous exposure and an improvement in sampling strategy can be established. This study shows that an administrative exposure registry can have a strong interactive role in channeling relevant risk information to the primary care provider.

ACKNOWLEDGMENTS

We wish to thank the occupational hygienists of the Department of Hygiene at the Institute for Occupational and Environmental Health who carried out the sampling and analysis which comprised the data for this article and to P. Goldberg from the same department for his valuable advice and comments.

APPENDIX

The mixed effects model:

The mixed effects model can be specified by the following expression:

$Yij=\beta 0+ \beta 1Xij1+ \ldots\ldots+ \beta pXijp+ b1Z1+\ldots\ldots+bkZk+\varepsilon ij$

i=1,.....,k (workers) j=1,.......,ni (repetitions of the i'th worker)

Yij= log-transformed values of benzene concentrations

$\beta 0$ = overall (fixed) group mean; mean of Yij

$\beta 1,\ldots\ldots, \beta p$ = fixed effects

Xij1, …........,Xijp= values for the i'th worker on the j'th repetition for each effect

b1,........,bk= workers' random effects

Z1,.......,Zk= workers' indicators (0/1)

The concentrations of the benzene were assumed to have a log-normal distribution.

$\varepsilon ij \sim N(0, \sigma^2 e)$ independent within a worker ; $bi \sim N(0, \sigma^2 b)$

εij's and bi's are all independent.

$E(Yij)= \mu i$ for specific i; for every j=1,.......,ni

$$var(Yij)=\begin{cases} \sigma^2 & i=j \\ \rho\sigma^2 & i\neq j \end{cases}$$ compound symmetry structure

$\rho=corr(\varepsilon il, \varepsilon im)$ for every i=1,.....k; l,m=1,.....,ni $l\neq m$

Exposure determinants were considered as fixed effects in the above model, as follows:

$\beta 0$ = background exposure (=intercept)

$\beta 1$ = task effect

$\beta 2$ = month effect

$\beta 3$ = day of the week effect

$\beta 4$ = credit-day effect

$\beta 5$ = period effect

Xij1= task indicator (0/1) for the i'th worker on the j'th repetition

0- non-filler, 1-filler.

Xij2= month indicator (0/1) for the i'th worker on the j'th repetition

0-non-warm months, 1-warm months (Jun,Jul,Aug,Sep).

Xij3= day of the week indicator (0/1) for the i'th worker on the j'th repetition

0- any day except Tuesday, 1-Tuesday.

Xij4= credit-day indicator (0/1) for the i'th worker on the j'th repetition

0- any day except credit-day 1-specific dates each month: 1,2,10,11,15,16,20,21,30,31.

Xij5= period indicator (0/1) for the i'th worker on the j'th repetition

0-1989-1992, 1-1993-1996.

REFERENCES

1. Savitz DS, Anderews KW. Review of epidemiologic and evidence on benzene and lymphatic and hematopoietic cancers. Am J Ind Med 1997;31:287-95.
2. Foo Swee Ceng. Benzene pollution from gasoline usage. Sci Total Environ 1991:103;19-26.
3. Fung KK, Wright BJ. Monitoring of benzene in ambient air with organic vapor badges. J of Air Pollution Control Assoc 1986:36; 819-21.
4. Lagorio S, Forastiere F, Iavarone N, et al. Exposure assessment in a historical cohort of filling stations attendants. Int J of Epidemiology 1993;s51-s56.
5. Rappaport SM, Selvin S. Exposure hydrocarbon components of gasoline in the petroleum industry. Appl Ind Hyg 1987;2:148-54.
6. Spear RC, Selvin S (personal communication) Benzene exposure in the petroleum refining industry. Appl Ind Hyg 1987;4:155-63.
7. Armstrong TW, Pearlman ED, Schnatter AR, et al. Retrospective benzene and total hydrocarbon exposure assessment for a petroleum marketing and distribution worker epidemiology study. Am Ind Hyg Assoc J 1996; 57:333-43.
8. Lewis SJ, Bell GM, Cordingley N, et al. Retrospective estimation of exposure to benzene in a leukaemia case-control study of petroleum marketing and distribution workers in the United Kingdom .Occup Environ Med 1997;54:167-75.
9. Irving WS, Grumbles TG. Benzene exposures during gasoline loading at bulk marketing terminals Am Ind Hyg Assoc J 1979;40:468-73.
10. Rushton L, Thar WE Retrospective exposure assessment for benzene; issues, methods and recommendations from an international workshop on petroleum marketing and distribution worker studies. Occupational Hygine 1996;5:295-305.
11. Verma DK, Julian JA, Bebee G, et al. Hydrocarbon exposures at petroleum bulk terminal and agencies. Am Ind Hyg Assoc J 1992;53:645-56.
12. Halder CA, Van-Gorp GS, Hatoum NS, et al. Gasoline vapor exposures. Part I. Characterization of workplace exposures Part II. Evaluation of the nephrotoxicity of the major c4/c5 hydrocarbon components. Am Ind Hyg Assoc J 1986;47:164-75.

13. Boleij J, Buringh E, Heederik D, et al. Occupational hygiene of chemical and biological agents. Elsevier, Amsterdam, The Netherlands, 1995.
14. Preller L, Kromhout H, Heederik D, et al. Modelling long-term average exposure - in occupational exposure-response analysis. Scand J Work, Environ, Health 1995;21:504-12
15. Rappaport SM. Assessment of long-term exposure to toxic substances in air. Ann Occup Hyg 1991;35:61-121.
16. Burstein I, Teschke K. Methodological considerations in studies of determinants of exposure. Am Ind Hyg Assoc J (accepted for publication).
17. Heederik D, Boleij JSM, Kromhout H, et al. Use and analysis of exposure monitoring data in occupational epidemiology: an example of an epidemiological study in the Dutch animal food industry. Appl Occup Environ Hyg 1991;5:458-64.
18. Kromhout H, Swuste P, Boleij JSM. Empirical modeling of chemical exposure in the rubber manufacturing industry. Ann Occup Hyg 1994;38:3-22.
19. Peretz C, Goldberg P, Kahan E, et al. The variability of exposure over time: a prospective longitudinal study. Ann Occup Hyg 1997;41:4:485-500.
20. Burdorf A. Shifting Concepts in Assessment of Occupational Exposures. Ann Occup Hyg 1993;37:447-50.
21. Dewell P. Technical Handbook Series No. 1: Some Application of Statistics in Occupational Hygiene. BOHS, British Occupational Hygiene Society Science Reviews Ltd with H & H Scientific Consultants, Leeds, UK, 1989.
22. Kromhout H, Symanski E, Rappaport SM. A comprehensive evaluation of within- and between- worker components of occupational exposure to chemical agents. Ann Occup Hyg 1993;37:253-70.
23. Nieuwenhuijsen MJ, Lowson D, Venable KM, et al. Flour dust exposure variability in flour mills and bakeries. Ann Occup Hyg 1995;39:299-305.
24. Francis M, Selvin S, Spear R, et al. The effect of autocorrelation on the estimation of worker's daily exposures. Am Ind Hyg Assoc J 1989;50:37-43.
25. Kumagai S, Kusaka Y, Goto S. Cobalt exposure level and variability in the hard metal industry of Japan. Am Ind Hyg Assoc J 1996;57:365-69.
26. Breslow NE, Clayton DG. Appoximate inference in generlaized linear models. J of American Statistical Association 1993; 88:9-25.
27. Lindskey JK. Models for repeated measurements Clarendon Press, Oxford, GB, 1993.
28. Searle SR. Mixed models and unbalanced data: wherefrom, whereat and whereto. Communication in Statistics-Theory and Methods 1988;17-24:935-968.
29. Searle SR, Casella G , et al. Variance Components , John Wily and Sons , New York USA, 1992.
30. SAS: SAS/ STAT software, changes and enhancements. SAS Institute , North Carolina USA, 1996.
31. Symanski E, Kupper LL, Kromhout H, et al. An investigation of systematic changes in occupational exposure. Am Ind Hyg Assoc J 1996;57:724-35.
32. Rappaport SM, Lyles RH, Kupper LL.An exposure assessment strategy accounting for within- and between worker sources of variability. Ann Occup Hyg 1995;39:469-95.
33. Rappaport SM, Kromhout H, Symanski E. Variation of exposure between workers in homogenous exposure groups. Am Ind Hyg Assoc J 1993;54:654-62.