Cross-shift changes in FEV₁ in relation to wood dust exposure: the implications of different exposure assessment methods

V Schlünssen, T Sigsgaard, I Schaumburg, H Kromhout

Occup Environ Med 2004;**61**:824–830. doi: 10.1136/oem.2003.011601

See end of article for authors' affiliations

Correspondence to:
Dr V Schlünssen,
Department of
Environmental and
Occupational Medicine,
University of Aarhus, DK-
8000 Aarhus C, Denmark;
vivi_schlunssen@dadlnet.
dk

Accepted 15 April 2004

Background: Exposure-response analyses in occupational studies rely on the ability to distinguish workers with regard to exposures of interest.

Aims: To evaluate different estimates of current average exposure in an exposure-response analysis on dust exposure and cross-shift decline in FEV₁ among woodworkers.

Methods: Personal dust samples (n = 2181) as well as data on lung function parameters were available for 1560 woodworkers from 54 furniture industries. The exposure to wood dust for each worker was calculated in eight different ways using individual measurements, group based exposure estimates, a weighted estimate of individual and group based exposure estimates, and predicted values from mixed models. Exposure-response relations on cross-shift changes in FEV₁ and exposure estimates were explored.

Results: A positive exposure-response relation between average dust exposure and cross-shift FEV₁ was shown for non-smokers only and appeared to be most pronounced among pine workers. In general, the highest slope and standard error (SE) was revealed for grouping by a combination of task and factory size, the lowest slope and SE was revealed for estimates based on individual measurements, with the weighted estimate and the predicted values in between. Grouping by quintiles of average exposure for task and factory combinations revealed low slopes and high SE, despite a high contrast.

Conclusion: For non-smokers, average dust exposure and cross-shift FEV₁ were associated in an exposure dependent manner, especially among pine workers. This study confirms the consequences of using different exposure assessment strategies studying exposure-response relations. It is possible to optimise exposure assessment combining information from individual and group based exposure estimates, for instance by applying predicted values from mixed effects models.

Exposure-response analyses in occupational studies rely heavily on the ability to reliably and accurately distinguish workers with regard to exposures of interest. Different approaches have been used, in order to maximise the validity of exposure assessment. Using an individual based approach for non-acute effects in general increases the precision of the exposure-response relation, but at the expense of introducing bias (attenuation).^{1,2} Conversely, a group based approach is in general unbiased but introduces a significant amount of error in the analyses.³ Seixas and Sheppard⁴ introduced an alternative exposure assessment strategy that uses the advantages of both an individual and group based approach. This strategy can however, only be applied when individual exposure measurement data are available for each study subject. In a recent paper by Heederik and Attfield⁵ on FEV₁ (forced expiratory volume in the first second) and cumulative dust exposure in the mining industry, it was shown that using the same measurement data in different ways had considerably impact on the exposure-response relations observed. Van Tongeren and colleagues⁶ found large effects on the slope and standard error of the exposure-response relation between FEV₁ and current dust exposure using different grouping schemes for estimating exposure in the carbon black industry.

Cross-shift FEV₁ by definition takes place during one specific day. Therefore one may argue, that exposure measured on that specific day will be the most appropriate estimate of the relevant exposure. We have earlier revealed an exposure-response relation between bronchial hyperresponsiveness and wood dust exposure, despite a time lag of

several months between exposure assessment and clinical examination, suggesting bronchial hyperresponsiveness to be related to average current exposure rather than acute exposure.⁷ Several studies have investigated the relation between cross-shift FEV₁ and wood dust exposure,^{8–14} and most of them revealed an acute obstructive decrease in lung function by exposure to wood dust. As far as we are aware, no one has explored the implications of using average exposure measures compared to concurrent individual exposure measures.

Recently, a cross-sectional epidemiological study has been undertaken to investigate the relation between wood dust exposure and respiratory impairment among workers in the furniture industry in Denmark. Among other health parameters, baseline lung function and cross-shift decline in FEV₁ were investigated.¹⁵ Until now, an individual based exposure assessment has been used in the data analysis.

The aim of this analysis was to evaluate the impact of alternative ways of estimating average exposure in an exposure-response analysis of dust exposure and cross-shift decline in FEV₁ among wood dust exposed workers.

Abbreviations: AM, arithmetic mean; GM, geometric mean; BWS_g^2 , between-workers variance; BGS_g^2 , between-group variance; WGS_g^2 , within-group variance; GSD, geometric standard deviation; FEV₁, forced vital capacity in one second; SD, standard deviation; SE, standard error; WWS_g^2 , within-worker variance in each group; BWS_g^2 , between-workers variance in each group; j , mean number of repeated samples in each group; B_g , weighting factor = $(WWS_g^2 \times (j-1)) / (BWS_g^2 + WWS_g^2 \times (j-1))$

Main messages

- There seems to be an association between average exposure and cross-shift changes in FEV₁ among non-smoking woodworkers, especially among pine workers.
- It is possible to combine information from an individual and a group based exposure assessment approach, in order to maximise the validity of exposure estimates in terms of both attenuation and precision.

Policy implications

- Cross-shift changes in lung function among woodworkers should not focus solely on current exposure, but should also take into account long term average exposure.

METHODS

Exposure assessment

A total of 2303 woodworkers from 54 furniture industries in Viborg County, Denmark, participated in the study, which took place between October 1997 and April 1998. For 1560 persons dust samples as well as data on lung function parameters were available. For 21 persons, repeated exposure measurements but no health data were available. They were included in the exposure assessment as well, making a total of 1581 persons and 2217 measurements. Figure 1 shows a flow chart of the investigation. The time interval between each sampling round was between 5 and 9 days.

Personal dust sampling was carried out with passive dust monitors described earlier.^{16,17} The method is based on measuring light extinction before and after sampling on transparent foils. The light extinction increase was reported as dust covered foil area, converted into equivalent inhalable dust concentration by linear regression models, based on earlier and present calibration samples.¹⁷ The mean (SD) duration of sampling was 255 (51) minutes.

On the day of dust sampling, information was collected on work task (sanding, cutting, sanding + cutting, assembly/

packing, other tasks, mixed tasks), degree of automation (full automatic, semi-automatic, manual) and use of compressed air (yes/no).

In total, 42% of woodworkers used mainly pinewood, 13% particle board or fibre board, and 6% different kinds of hard wood, mainly beech. The rest, 39%, used a mixture of different wood species.

Exposure to wood dust for each worker was calculated in several ways.

Method 1

Using the dust sample collected for each individual on the same day as lung function was measured (individual, 1. round). For 1541 individuals, dust measurements from first sampling round were available, see fig 1.

Method 2

Calculating an individual arithmetic mean exposure per person using all samples from individuals with a first sampling round measurement available, a total of 1541 individuals and 2181 measurements (individual, all rounds), see fig 1.

Method 3

Using the quartiles of the distribution of the individual arithmetic mean exposure from method 2 to create four

Figure 1 Flow chart of the study.

groups, with similar number of samples (individual, four groups).

Methods 4–5

Estimation of the most efficient grouping strategy.

The following grouping variables were explored: task, degree of automation, factory size (dichotomised <200/≥200 employees), use of compressed air, combination of task and factory size, and combination of task and factory. For each group, the median (geometric mean) of the individual arithmetic mean distribution was calculated.

Additionally, five exposure groups were formed, by ranking all combinations of factory and task categories according to the arithmetic mean exposure. The quintiles of this distribution were chosen as cut off points.

Contrast in mean exposure levels between groups was calculated as described by Kromhout and Heederik¹⁸ using formula 1:

$$\text{Contrast} = \text{BG}S_y^2 / (\text{BG}S_y^2 + \text{WG}S_y^2), \quad (1)$$

where $\text{BG}S_y^2$ is the between-group and $\text{WG}S_y^2$ the within-group variance.

Method 6

For the grouping based on the combination of task and factory size a weighted estimate was calculated based on the James-Stein shrinkage estimator, first described by James and Stein,¹⁹ and further developed to be group specific by Seixas and Sheppard.⁴ For each of the 12 groups based on a combination of task and factory size, a weighting factor Bg was calculated using formula 2:

$$\text{Bg} = (\text{wWS}_g^2 \times (j^{-1})) / (\text{BWS}_g^2 + \text{wWS}_g^2 \times (j^{-1})) \quad (2)$$

where wWS_g^2 is the within-worker variance, BWS_g^2 the between-workers variance, and j the mean number of repeated samples in each group. A weighted mean of group based and individual based exposure estimates were calculated using the following formula:

$$\text{Weighted mean} = (\text{Bg} \times \text{group mean}) + ((1 - \text{Bg}) \times \text{individual mean}), \quad (3)$$

Where “group mean” is the group mean estimated under method 4 and “individual mean” is the mean estimated under method 2.

Methods 7–8

Dust exposure was modelled with two mixed effects models, and predictions from each models were used as measures of exposure. The first model included significant determinants of dust exposure as fixed effects and worker and factory as random effects. The following variables were included: task, degree of automation, use of compressed air, work at night shift and safety representative elected within the last two years. Additionally, the interaction term “assembly/handling × manual work” was included in the model. The second model included the combination of task and factory size as fixed effect and worker as random effect.

Lung function

Pulmonary function was tested using a dry spirometer (Vitalograph, Buckingham, UK) on a random day during the week at the same day as dust measurements were performed. Among others, FEV₁ was measured. Testing was performed in accordance with international guidelines.²⁰ Height and weight were measured before the lung function test. For 1293 subjects, lung function was measured both before and after work. The percentage difference (cross-shift FEV₁) was calculated as pre-shift minus post-shift, divided by the largest measured FEV₁, multiplied by 100.

From a self administered questionnaire, information about smoking, age, gender, sideline occupation, lung diseases, previous dusty non-woodworking jobs, and seniority in the wood industry, was collected.

Statistical analyses

As the data were lognormal distributed, analyses were performed with log transformed data with SAS System for Windows version 8.0.

Nested one way analysis of variance (ANOVA) was used to estimate within (wWS_y^2) and between worker (BWS_y^2) components of variance.²¹ Nested two way ANOVA was used to estimate the within (wGS_y^2) and between group (BGS_y^2) variability.¹⁸

The mixed models were elaborated with PROC MIXED.

The relation between exposure and lung function variables was analysed in SPSS for Windows, version 10.0, using least square regression. As dependent variable, the adjusted (for age, height, gender) residuals of cross-shift FEV₁ were used. Dust exposure, smoking, body mass index, and wood species were included in the final models.

All participating subjects gave informed consent, and the protocol has been approved by the Ethics Committee for Viborg County, Denmark.

RESULTS

Table 1 presents the number of measurements, the GM (geometric mean), and GSD (geometric standard deviation) for dust exposure in the three sampling rounds. No difference was seen between the three rounds, with an overall GM (GSD) of 0.96 mg/m³ (2.05).

The overall ratio of within- to between-worker variance was: 0.275/0.269 = 1.02. In table 2, variance components and contrast for different grouping strategies are given. Grouping according to the combination of task and factory size (“12 categories”) and the quintiles of the combination of task and factory (“5 categories”) revealed highest contrast in exposure between groups, 0.51 and 0.64 respectively. Grouping by automation and use of compressed air both revealed contrast below 0.1.

Figure 2 presents mean dust level and number of persons in each group for the combination of task and factory size (fig 2A) and the quintiles of the combination of task and factory (fig 2B). The number of persons in each group was highly unequally distributed, and ranged from 5 to 429 for the combination of task and factory size and between 179 to 390 in the quintiles for the combination of task and factory.

Table 3 shows the correlation coefficients between the eight exposure parameters. High correlation coefficients were seen between the three methods using individual samples ($r > 0.84$). Additionally, high correlations were seen between individual samples, weighted mean, mixed model 1, and mixed model 2 ($r > 0.81$). The lowest correlation was seen between the individual samples and “12 categories” ($r < 0.43$). All correlations were highly significant at the $p < 0.001$ level.

Table 1 Inhalable dust concentration (mg/m³) for measurements in three sampling rounds

Sampling round	n	GM (GSD)
1	1541	0.93 (2.11)
2	351	0.94 (2.11)
3	325	0.97 (1.99)
Total	2217	0.96 (2.05)

n, number of measurements; GM, geometric mean; GSD, geometric standard deviation.

Table 2 Variance components and contrast using different grouping strategies

	Number of groups	BG S_y^2	WG S_y^2	WW S_y^2	TOTAL S_y^2	Contrast
Tasks	6	0.089	0.208	0.264	0.558	0.300
Automation	4	0.009	0.263	0.275	0.547	0.033
Factory size	2	0.053	0.259	0.275	0.586	0.170
Use of compressed air	2	0.038	0.348	0.275	0.562	0.098
Factory	54	0.062	0.210	0.275	0.546	0.228
Task + factory size	12	0.139	0.136	0.263	0.538	0.505
Task + factory	246*	0.142	0.134	0.2635	0.539	0.514
Task + factory, quintiles	5	0.204	0.115	0.263	0.582	0.639

BG S_y^2 , between-group variance; WG S_y^2 , within-group variance; WW S_y^2 , within-worker variance; TOTAL S_y^2 , total variance.

Contrast in exposure between groups: BG S_y^2 /BG S_y^2 + WG S_y^2 .

*A total of 324 groups was possible. For 78 groups no measurements were available, leaving 246 groups for the analysis.

Table 4 gives results of linear regression on exposure estimates and cross-shift FEV₁. No statistically significant ($p < 0.05$) relations were shown, irrespective of which exposure estimate was used. However, the size of the effect (slope) was 70% higher for “12 categories”, than for individual estimates on the day of the lung function testing. As expected, the standard error (SE) of coefficients was increased in grouping estimates compared to individual estimates. The weighted estimate and mixed model 2 had slopes and standard errors in between individual and grouping estimates. Mixed model 1 and “5 categories” had the lowest slopes.

Table 5 shows results of linear regression on exposure estimates and cross-shift FEV₁, stratified by smoking and further by smoking and use of pine. A statistically significant positive association between dust exposure and cross-shift FEV₁ was revealed for non-smoking woodworkers for all exposure estimates except “5 categories” and “mixed model 1”. Further stratification by pine revealed a stronger association for pine workers compared to woodworkers using other species, although the difference between the slopes did not reach the level of 95% significance.

No relation between dust exposure and cross-shift FEV₁ was seen for smokers, irrespective of the chosen measures of exposure.

Among non-smokers, the highest slope and SE was revealed for “12 categories”. The lowest slope and SE was seen for the individual estimates and for “5 categories”, with the weighted estimate and mixed model 2 having slopes and SE in between. Among non-smoking pine workers the same tendency was seen, except for “12 categories” with a slope comparable to the individual estimates. The weighted estimate and mixed model 2 achieved the highest slopes.

The distribution of dust among smokers and non-smokers, and among pine workers and non-pine workers was explored, revealing no overall significant differences.

Using different estimates of exposure only marginally changed the slopes for other variables in the models—that is, smoking, wood species, and body mass index (data not shown). The non-pine workers used quite different wood species. No difference was observed when the relation between dust exposure and cross-shift FEV₁ was stratified by these wood species.

DISCUSSION

We revealed associations between exposure to dust in wood manufacturing and cross-shift decline in FEV₁ among non-smoking woodworkers, especially among pine workers.

Several studies revealed an acute obstructive decrease in lung function by exposure to wood dust, but only Mandryk and colleagues⁸ performed a substantial number of measurements. They found an exposure-response relation between cross-shift decline in FEV₁ and 163 inhalable dust measurements from mixed wood species. Lung function and dust measurements were performed on the same work day. Beritic-Stahuljak and colleagues⁹ found an exposure-response relation between cross-shift decline in FEV₁ and exposure to softwood (mainly pine) but not to hardwood. In some studies cross-shift decline in FEV₁^{10–12} was found among workers exposed to wood dust, compared to non-exposed subjects. A few studies did not find any relation between exposure to wood dust and cross-shift FEV₁.^{13 14}

We have earlier shown increased coughing among woodworkers, most pronounced in non-smokers.¹⁵ It may be that

Figure 2 Mean dust level and number of persons in each group for grouping “task + factory size” (A), and “task + factory, quintiles” (B).

Table 3 Pearson's correlation coefficient *r* for eight exposure estimates for current average exposure

	1. Individual, 1. round	2. Individual, all rounds	3. Individual, 4 groups	4. 12 categories	5. 5 categories	6. Weighted estimate	7. Mixed model 1	8. Mixed model 2
1. Individual, 1. round	1.000	0.954	0.845	0.417	0.540	0.885	0.882	0.905
2. Individual, all rounds		1.000	0.877	0.423	0.558	0.923	0.904	0.932
3. Individual, 4 groups			1.000	0.424	0.567	0.816	0.830	0.849
4. 12 categories				1.000	0.625	0.665	0.632	0.684
5. 5 categories					1.000	0.629	0.709	0.667
6. Weighted estimate						1.000	0.916	0.959
7. Mixed model 1							1.000	0.957
8. Mixed model 2								1.000

Number of woodworkers: 1422. The estimates are labelled according to the method number.
All correlation coefficients are significant with $p < 0.001$, two tailed.

the massive effect of smoking “masks” the effect of wood dust. In fact, a “healthy smoker effect” has been suggested earlier.²²

Differences in slope and SE of exposure-response relations were revealed, depending on how exposure measurements were treated in the exposure assessment. Increased slopes and increased SE were found for the group based estimates using task and factory size as grouping variable. Despite a larger contrast in the grouping with five categories formed by ranking all combinations of task and factory, this estimate resulted in a decreased slope, compared to the other group based exposure estimates. This is most likely due to unequal distribution of samples in each of the 246 groups, with 80 groups only containing one sample, and the largest group comprising 65 samples. This will have resulted in very imprecise estimates of average exposure for a considerable amount of the 246 groups.²³ Even though a grouping strategy was used in this approach, considerable misclassification error could not be prevented.

Grouping by “12 categories” revealed a decreased slope for pine workers compared to non-pine workers, suggesting a less efficient grouping for pine workers. One explanation may be an impact of terpene exposure on cross-shift decline in lung function among pine exposed workers. Terpenes are naturally occurring substances in pine wood.²⁴ Irritation to mucous membranes and impairment in lung function has been documented.^{25–27} The documentation on terpene exposure in the dry wood industry (for example, furniture industry, joineries) is sparse. Eriksson *et al* found chronic impairment in lung function among joinery workers compared to controls, and ascribe the effect mainly to terpenes.²⁸ Unfortunately, we were not able to explore the impact of terpene exposure in this study.

Table 4 Adjusted linear regression on cross-shift decline in FEV₁ (the residuals adjusted for age, gender, and height) and dust exposure (1156 individuals)

RES cross-shift FEV ₁ *			
Exposure estimates	Coefft	SE	p value
1. Individual, 1. round	0.397	0.23	0.09
2. Individual, all rounds	0.403	0.25	0.10
3. Individual, 4 groups	0.369	0.29	0.20
4. 12 categories	0.681	0.58	0.24
5. 5 categories	0.161	0.39	0.68
6. Weighted estimate	0.631	0.39	0.10
7. Mixed model 1	0.199	0.40	0.62
8. Mixed model 2	0.565	0.41	0.17

The estimates are labelled according to the method number.

Numbers may vary due to missing values.

*Variables included in the final model: dust exposure, use of beech, pack-year, and body mass index.

†Unit: percentage decline in FEV₁/mg/m³ dust.

The weighted estimate based on the group specific (a combination of task and factory size) James-Stein shrinkage estimator and predictions from mixed model 2 (including task and factory size as fixed effects and worker as random effect) resulted in similar estimates of slope and SE. This is not surprising, since the predicted values using PROC MIXED are achieved using empirical Bayes' estimates including fixed and random effects,²⁹ which is basically similar to the James-Stein shrinkage method as described by Seixas and Sheppard.⁴ By using information that distinguishes the individual from the group and information about the group that makes it an identifiable unit, it seems possible to maximise the validity of measurements in terms of both attenuation and precision.

Estimates of average exposure including non-acute determinants for exposure resulted in highest slopes. Our results indicate that cross-shift changes in FEV₁ are not only determined by actual exposure level, but also are determined by chronic exposure. This suggests an “irritation effect” of wood dust on the respiratory mucosa not disappearing at the end of the working day, and this may “prime” the lungs for the acute effect.

In order to be able to generalise the model outside the actual study, factory was included as a random effect in mixed model 1. As a consequence, it was not possible to include factory size as an explanatory variable. This was the most influential difference between mixed model 1 and 2, which probably explains why mixed model 1 seems to predict exposure in a less appropriate way, even though more explanatory variables were included. Thus, by leaving out factory specific determinants (that is, factory size), the generalisation of the model is increased, but results in a less sufficient model.

The study by Scheeper and colleagues³⁰ is to our knowledge the only other study in the wood industry, where the ratio of within- to between-worker variance has been explored. In that study, exposure was measured for two randomly selected days or five consecutive days. Within-worker variance was 1.11 times the between-worker variance. The within- to between-worker ratio of variance in this study was 1.02, which was in accordance with our previous findings among the 293 woodworkers with three repeated samples.³¹ Repeated measurements with short time lag of one week might be influenced by autocorrelation and a possible bias of the variances towards smaller values may be present. Symanski and Rappaport³² however showed that this trend was only presented in a minor part of the series analysed.

Both within- and between-worker variability in exposure concentrations in this study were relatively low compared to earlier studies comprising data on variance components,^{2,3} suggesting a relatively uniform exposure to wood dust. The overall GM and GSD in the present study were lower compared to an earlier cross-sectional study in the Danish

Table 5 Adjusted linear regression on cross-shift decline in FEV₁ (the residuals adjusted for age, gender, and height), and dust exposure

Exposure estimates	RES cross-shift FEV ₁ *											
	+ smoking (n = 497)			- smoking (n = 639)			- smoking, - pine (n = 378)			- smoking, + pine (n = 260)		
	Coeff.†	SE	p value	Coeff.†	SE	p value	Coeff.†	SE	p value	Coeff.†	SE	p value
1. Individual, first round	-0.060	0.35	0.86	0.821	0.32	0.01	0.522	0.40	0.19	1.230	0.53	0.02
2. Individual, all rounds	0.022	0.37	0.95	0.792	0.34	0.02	0.343	0.41	0.42	1.474	0.57	0.01
3. Individual, 4 groups	-0.027	0.46	0.95	0.829	0.38	0.03	0.130	0.48	0.79	1.569	0.55	<0.01
4. 12 categories	-0.836	0.90	0.36	1.636	0.77	0.03	2.016	1.01	0.05	1.270	1.22	0.30
5. 5 categories	-0.143	0.60	0.81	0.296	0.53	0.57	0.046	0.66	0.94	0.799	0.88	0.36
6. Weighted estimate	-0.314	0.59	0.59	1.336	0.53	0.01	0.895	0.65	0.17	2.050	0.90	0.02
7. Mixed model 1	-0.479	0.59	0.42	0.801	0.57	0.16	0.248	0.71	0.73	1.631	0.93	0.08
8. Mixed Model 2	-0.247	0.62	0.69	1.248	0.56	0.03	0.696	0.71	0.33	2.020	0.92	0.03

Stratified by smoking and by use of pine. The estimates are labelled according to the method number.
n = number of persons. Numbers may vary due to missing values.
*Variables included in the final models: dust exposure, use of beech, body mass index.
†Unit: percentage decline in FEV₁/mg/m³ dust.

furniture industry,¹⁷ suggesting that control measures introduced in the recent past have successfully reduced mean dust levels, possibly by controlling the most extreme exposure situations.

The contrast for grouping by “task” and by “task and factory size” was 0.30 and 0.51, respectively. Kromhout and colleagues³ estimated contrast between 0.15 (job) and 0.57 (plant) for wood manufacturing in one furniture factory and three joineries, based on data from Scheeper and colleagues.³⁰ Van Tongeren and colleagues⁶ found a high contrast (0.75) in the carbon black industry grouping inhalable dust samples by job and plant. Contrasts in occupational exposure in several other industries were between 0.00 and 0.61 (job) and between 0.21 and 0.84 (job and plant combination),²¹ making the contrasts in our study an “average” contrast in occupational settings.

Of the total variance and between-worker variance respectively 26% and 17% was accounted for using determinants of exposure, which is in accordance with results from a subpopulation of the study group.³³ The explainable part of the variation is lower than stated in earlier studies modelling wood dust exposure using conventional linear regression models^{30–34} or mixed models including within-worker variation,³⁵ and also when compared to other studies related to airborne particular contaminants.³⁶ Personal exposure to wood dust contains contributions from many sources in the production facilities, for example, the machine present, other machines in the vicinity, dust carried by recirculated air, or dust resuspended by compressed air or by sweeping. The relatively low overall GM and GSD in this study suggests that indirect sources are important for exposure, and determinants for indirect exposure were hardly included in our model. Scheeper and colleagues³⁰ documented that differences between background exposures and near source exposures decrease with decreasing levels of exposure.

In conclusion, there seems to be an association between dust exposure and cross-shift changes in FEV₁ among non-smoking woodworkers, especially among pine workers. Studies in the dry wood industry including personal samples on both terpenes and dust exposure are needed in order to explore the combined impact of wood dust and terpenes on temporal changes in lung function.

This study confirms the consequences of using different exposure assessment strategies studying exposure-response relations. Our results suggest that it is possible to combine information from an individual and a group based exposure assessment approach, in order to maximise the validity of exposure estimates in terms of both attenuation and precision.

ACKNOWLEDGEMENTS

The study was supported by The Danish Work Environment Foundation; Viborg County; The Danish Medical Research Council; The Wood Industry and Building Workers Union in Denmark; The Danish Lung Association; The Asthma and Allergy Association; and The Health Insurance Fund.

Authors’ affiliations

V Schlünssen, T Sigsgaard, Department of Environmental and Occupational Medicine, University of Aarhus, DK-8000 Aarhus C, Denmark
I Schaumburg, Department of Occupational and Environmental Medicine, Skive Hospital, Resenvej 25, DK-7800 Skive, Denmark
H Kromhout, Institute for Risk Assessment Sciences (IRAS), Division of Environmental and Occupational Health, Utrecht University, NL 3512 Utrecht, Netherlands

REFERENCES

- 1 **Armstrong BG**. Effect of measurement error on epidemiological studies of environmental and occupational exposures. *Occup Environ Med* 1998;**55**:651–6.
- 2 **Tielemans E**, Kupper LL, Kromhout H, *et al*. Individual-based and group-based occupational exposure assessment: some equations to evaluate different strategies. *Ann Occup Hyg* 1998;**42**:115–19.
- 3 **Kromhout H**, Tielemans E, Preller L, *et al*. Estimates of individual dose from current measurements of exposure. *Occup Hyg* 1996;**3**:23–39.
- 4 **Seixas NS**, Sheppard L. Maximizing accuracy and precision using individual and grouped exposure assessments. *Scand J Work Environ Health* 1996;**22**:94–101.
- 5 **Heederik D**, Attfield M. Characterization of dust exposure for the study of chronic occupational lung disease: a comparison of different exposure assessment strategies. *Am J Epidemiol* 2000;**151**:982–90.
- 6 **Van Tongeren MJ**, Kromhout H, Gardiner K, *et al*. Assessment of the sensitivity of the relation between current exposure to carbon black and lung function parameters when using different grouping schemes. *Am J Ind Med* 1999;**36**:548–56.
- 7 **Schlünssen V**, Schaumburg I, Heederik D, *et al*. Indices of asthma among atopic and non-atopic woodworkers. *Occup Environ Med* 2004;**61**:504–11.
- 8 **Mandryk J**, Alwais KU, Hocking AD. Work-related symptoms and dose-response relationships for personal exposures and pulmonary function among woodworkers. *Am J Ind Med* 1999;**35**:481–90.
- 9 **Beritic-Stahuljak D**, Valic F, Cigula M, *et al*. Aerosol analysis, respiratory function and skin sensitivity testing in workers exposed to soft and hardwood dust. *Arh Hig Rada Toksikol* 1988;**39**:387–403.
- 10 **Holness DL**, Sass-Kortsak AM, Pilger CW, *et al*. Respiratory function and exposure-effect relationships in wood dust-exposed and control workers. *J Occup Med* 1985;**27**:501–6.
- 11 **Al-Zuhair YS**, Whitaker CJ, Cinkotai FF. Ventilatory function in workers exposed to tea and wood dust. *Br J Ind Med* 1981;**38**:339–45.
- 12 **Herbert FA**, Hessel PA, Melenka LS, *et al*. Pulmonary effects of simultaneous exposures to MDI formaldehyde and wood dust on workers in an oriented strand board plant. *J Occup Environ Med* 1995;**37**:461–5.
- 13 **Goldsmith DF**, Shy CM. An epidemiologic study of respiratory health effects in a group of North Carolina Furniture workers. *J Occup Med* 1988;**30**:959–65.
- 14 **Ahman M**, Persson L, Lagerstrand L. Lung function in woodworking teachers in Sweden. *Int J Occup Environ Health* 1996;**2**:204–10.
- 15 **Schlünssen V**, Schaumburg I, Taudorf E, *et al*. Respiratory symptoms and lung function among Danish woodworkers. *J Occup Environ Med* 2002;**44**:82–98.

- 16 **Vinzens PS**. A passive personal dust monitor. *Ann Occup Hyg* 1996;**40**:261–80.
- 17 **Schlünssen V**, Vinzens PS, Mikkelsen AB, *et al*. Wood dust exposure in the Danish furniture industry using conventional and passive monitors. *Ann Occup Hyg* 2001;**45**:157–64.
- 18 **Kromhout H**, Heederik D. Occupational epidemiology in the rubber industry: implications of exposure variability. *Am J Ind Med* 1995;**27**:171–85.
- 19 **James W**, Stein C. Estimation with quadratic loss. In: *Proceedings of the Fourth Berkeley Symposium on Mathematical Statistics and Probability*. Berkeley, CA: University of California Press, 1961:361–80.
- 20 **Quanjer PH**, Tammeling GJ, Cotes JE, *et al*. Lung volumes and forced ventilatory flows. Report of the Working Party Standardization of Lung Function Tests, European Community for Steel and Coal. Official Statement of the European Respiratory Society. *Eur Respir J Suppl* 1993;**16**:5–40.
- 21 **Kromhout H**, Symansky 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.
- 22 **Becklake MR**, Laloo U. The “healthy smoker”: a phenomenon of health selection. *Respiration* 1990;**57**:137–44.
- 23 **Heederik D**, Kromhout H, Braun W. The influence of random exposure estimation error on the exposure-response relationship when grouping into homogeneous exposure categories. *Occup Hyg* 1996;**3**:229–41.
- 24 **Sjöström E**. *Wood chemistry, Fundamentals and applications*, 2nd edn. San Diego, CA: Academic Press, 1981.
- 25 **Kasanen J-P**, Pasanen A-L, Pasanen P, *et al*. Evaluation of sensory irritation of (delta)³-carene and turpentine, and acceptable levels of monoterpenes in occupational and indoor environment. *J Toxicol Environ Health* 1999;**56**:89–114.
- 26 **Hedenstierna G**, Alexandersson R, Wimander K, *et al*. Exposure to terpenes: effects on pulmonary function. *Int Arch Occup Environ Health* 1983;**51**:191–8.
- 27 **Filipsson AF**. Short term inhalation exposure to turpentine: toxicokinetics and acute effects in men. *Occup Environ Med* 1996;**53**:100–5.
- 28 **Eriksson KA**, Levin JO, Sandstrom T, *et al*. Terpene exposure and respiratory effects among workers in Swedish joinery shops. *Scand J Work Environ Health* 1997;**23**:114–20.
- 29 **Littell RC**, Miliken GA, Stroup WW, *et al*. Random coefficient models. In: *SAS system for mixed models*. Cary, NC: SAS Institute Inc, 1996:253–66.
- 30 **Scheeper B**, Kromhout H, Boleij JS. Wood dust exposure during wood-working processes. *Ann Occup Hyg* 1995;**39**:141–54.
- 31 **Vinzens PS**, Schlünssen V, Feveile H, *et al*. Variation in exposure to inhalable wood dust in the Danish furniture industry. Within- and between-workers and factory components estimated from passive dust sampling. *Ann Occup Hyg* 2001;**45**:603–8.
- 32 **Symansky E**, Rappaport SM. An investigation of the dependence of exposure variability on the interval between measurements. *Ann Occup Hyg* 1994;**38**:361–72.
- 33 **Mikkelsen AB**, Schlünssen V, Sigsgaard T, *et al*. Determinants of wood dust exposure in the Danish furniture industry. *Ann Occup Hyg* 2002;**46**:673–85.
- 34 **Alwis U**, Mandryk J, Hocking AD, *et al*. Dust exposures in the wood processing industry. *Am Ind Hyg Assoc J* 1999;**60**:641–6.
- 35 **Teschke K**, Demers PA, Davies HW, *et al*. Determinants of exposure to inhalable particulate, wood dust, resin acids, and monoterpenes in a lumber mill environment. *Ann Occup Hyg* 1999;**43**:247–55.
- 36 **Burstyn I**, Teschke K. Studying the determinants of exposure: a review of methods. *Am Ind Hyg Assoc J* 1999;**60**:57–72.