Annals of Work Exposures and Health, 2017, Vol. 61, No. 4, 416–428
doi: 10.1093/annweh/wxx020
Advance Access publication 9 March 2017
Original Article

BOHS The Chartered Society for Worker Health Protection
OXFORD

Original Article

Wood Dust in Joineries and Furniture Manufacturing: An Exposure Determinant and Intervention Study

Jeroen Douwes[1]*, Kerry Cheung[1], Bradley Prezant[1], Mark Sharp[2], Marine Corbin[1], Dave McLean[1], Andrea 't Mannetje[1], Vivi Schlunssen[3,4], Torben Sigsgaard[3], Hans Kromhout[5], Anthony D. LaMontagne[6], Neil Pearce[1,7] and James D. McGlothlin[2]

[1]Centre for Public Health Research, Massey University, Private Box 756, Wellington, New Zealand; [2]School of Health Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907, USA; [3]Department of Public Health, Aarhus University, Bartholins Alle 2, 8000 Aarhus C, Denmark; [4]National Research Centre for the Working Environment, Lerso Parkalle 105, Copenhagen DK-2100, Denmark; [5]Institute for Risk Assessment Sciences, Utrecht University, PO Box 80.178, NL-3508 TD Utrecht, The Netherlands; [6]School of Health and Social Development, Deakin University, Burwood, Victoria 3125, Australia; [7]Department of Medical Statistics, London School of Hygiene and Tropical Medicine, Keppel Street, London WC1E 7HT, UK

*Author to whom correspondence should be addressed. Tel: +64-4-38006017; fax: +64-4-3800600; e-mail: J.Douwes@massey.ac.nz

Submitted 22 August 2016; revised 13 February 2017; editiorial decision 13 February 2017; revised version accepted 19 February 2017.

Abstract

Objectives: To assess wood dust exposures and determinants in joineries and furniture manufacturing and to evaluate the efficacy of specific interventions on dust emissions under laboratory conditions. Also, in a subsequent follow-up study in a small sample of joinery workshops, we aimed to develop, implement, and evaluate a cost-effective and practicable intervention to reduce dust exposures.
Methods: Personal inhalable dust (n = 201) was measured in 99 workers from 10 joineries and 3 furniture-making factories. To assess exposure determinants, full-shift video exposure monitoring (VEM) was conducted in 19 workers and task-based VEM in 32 workers (in 7 joineries and 3 furniture factories). We assessed the efficacy of vacuum extraction on hand tools and the use of vacuum cleaners instead of sweeping and dry wiping under laboratory conditions. These measures were subsequently implemented in three joinery workshops with 'high' (>4 mg m^{-3}) and one with 'low' (<2 mg m^{-3}) baseline exposures. We also included two control workshops (one 'low' and one 'high' exposure workshop) in which no interventions were implemented. Exposures were measured 4 months prior and 4 months following the intervention.
Results: Average (geometric means) exposures in joinery and furniture making were 2.5 mg m^{-3} [geometric standard deviations (GSD) 2.5] and 0.6 mg m^{-3} (GSD 2.3), respectively. In joinery work-

ers cleaning was associated with a 3.0-fold higher ($P < 0.001$) dust concentration compared to low exposure tasks (e.g. gluing), while the use of hand tools showed 3.0- to 11.0-fold higher ($P < 0.001$) exposures. In furniture makers, we found a 5.4-fold higher exposure ($P < 0.001$) with using a table/circular saw. Laboratory efficiency experiments showed a 10-fold decrease in exposure ($P < 0.001$) when using a vacuum cleaner. Vacuum extraction on hand tools combined with a downdraft table reduced exposures by 42.5% for routing ($P < 0.1$) and 85.5% for orbital sanding ($P < 0.001$). Following intervention measures in joineries, a borderline statistically significant ($P < 0.10$) reduction in exposure of 30% was found in workshops with 'high' baseline exposures, but no reduction was shown in the workshop with 'low' baseline exposures.

Conclusions: Wood dust exposure is high in joinery workers and (to a lesser extent) furniture makers with frequent use of hand tools and cleaning being key drivers of exposure. Vacuum extraction on hand tools and alternative cleaning methods reduced workplace exposures substantially, but may be insufficient to achieve compliance with current occupational exposure limits.

Keywords: exposure; intervention; joinery workers; video exposure monitoring; wood dust

Introduction

Exposure to wood dust is associated with an increased risk of nasal and sino-nasal cancers (IARC, 1995), and highly exposed workers may also have an increased risk of lung cancer (Barcenas *et al.*, 2005; Jayaprakash *et al.*, 2008). Non-malignant respiratory effects also occur, generally at levels well below those considered to increase the risk of malignant effects (Demers *et al.*, 1995), including upper and lower respiratory tract symptoms and inflammation, impaired lung function, increased bronchial responsiveness, and occupational asthma (Bohadana *et al.*, 2000; Douwes *et al.*, 2001; Borm *et al.*, 2002; Douwes *et al.*, 2006). These effects have been demonstrated in a wide range of wood processing industries including joinery and furniture workers (Shamssain, 1992; Talini *et al.*, 1998; Schlunssen et al., 2002, 2004; Jacobsen *et al.*, 2008).

A study including exposure data from 25 European Union member states estimated that 3.6 million workers, or 2.0% of the total employed population, are exposed to inhalable wood dust (Kauppinen *et al.*, 2006). It also showed that in the furniture-manufacturing industry, 59% were exposed to inhalable wood dust and of those, 59% were exposed to levels in excess of 1 mg m^{-3}, a widely accepted international standard (ACGIH, 2016). In the joinery industry, 71% were exposed, with 52% exposed to levels in excess of 1 mg m^{-3} (Kauppinen *et al.*, 2006). The authors suggested that effective control measures to reduce wood dust exposure (and associated health risks) in joinery and furniture workers were therefore urgently needed.

Exhaust ventilation in joinery and furniture manufacturing has been shown to reduce dust concentrations, while specific tasks and work processes including sanding, use of compressed air, use of hand tools, use of fully automated machines, dry wiping and cleaning, and small size of workshop (<20 workers) may increase wood dust exposures (Scheeper *et al.*, 1995; Brosseau *et al.*, 2001; Rongo *et al.*, 2002; Schlunssen *et al.*, 2008). Significantly reduced exposures associated with local exhaust ventilation for hand tools tested under laboratory conditions has also been shown (Hampl and Johnston, 1985; Thorpe and Brown, 1994), but few interventions studies specific to wood dust and the woodworking industry have been conducted (Martin and Zalk, 1997; Brosseau *et al.*, 2001; Lazovich *et al.*, 2002; Brosseau *et al.*, 2002). A small study in a single joinery shop involving changes in local exhaust ventilation, cleaning methods, guidelines for using sanding tools, and the use of a downdraft table showed that exposures of less than 1 mg m^{-3} are achievable, but at a significant cost (Martin and Zalk, 1997). In contrast, a larger study in 48 small woodworking businesses half of which underwent a tailored mix of interventions including improved ventilation and use of administrative methods to control wood dust, and worker training to modify work practices, showed only a 10% (not statistically significant) decrease in dust levels.

Effective interventions should ideally be based on a detailed understanding of exposure determinants. Traditional 8-h time-weighted average (TWA) exposures generally provide insufficient detail as peak exposures cannot usually be linked directly to specific tasks and/or working conditions. Video exposure monitoring (VEM) that enables a graphical representation of a worker's exposure (as measured by a direct reading monitor) to be displayed on a video recording of the worker's activities is more suitable as it allows the identification of peak exposures and underlying determinants in real time (Rosén *et al.*, 2005). Nonetheless, despite its considerable potential, VEM is not often used for the development and evaluation of exposure reduction interventions.

The objectives of the study were to (i) assess inhalable wood dust exposure levels in New Zealand joineries and furniture manufacturing; (ii) assess exposure determinants using VEM; (iii) evaluate the efficacy of specific interventions on dust emissions under laboratory conditions; and (iv) to develop, implement, and evaluate (in a small sample of workshops) a cost-effective and practicable intervention to reduce exposures in joinery workers.

Materials and Methods

Study design

This study involved a survey in joinery workshops and furniture factories to assess inhalable dust exposures and its determinants using full-shift 8-h TWA exposure measurements and real-time VEM, respectively. Based on these results, we developed an intervention strategy that was tested in laboratory conditions followed by the implementation and evaluation of these measures in three high exposure workshops and one low exposure workshop (as determined in the exposure survey; Fig. 1). One workshop with high exposure and one with low exposure, where no intervention measures were introduced, were also included as internal controls. To assess the effects of the intervention, exposure measurements were conducted prior and after implementing the interventions (Fig. 1).

Recruitment

Joinery workshops and furniture manufacturers, identified through industry association websites and yellow pages, were recruited from the Wellington, Auckland, Hawkes Bay, Christchurch, and Southland regions of New Zealand. We randomly contacted 30 factories/workshops in these regions, of which 13 took part in the study (10 joineries and 3 furniture-making factories) with a combined total of 99 workers agreeing to participate. As is typical for this industry in New Zealand, joineries were relatively small, employing two to eight workers, whereas the furniture factories each employed >20 workers (Table 1). Although we expect that the recruited workshops and factories are reasonably representative for the New Zealand joinery and furniture-making industries respectively, this was not formally tested.

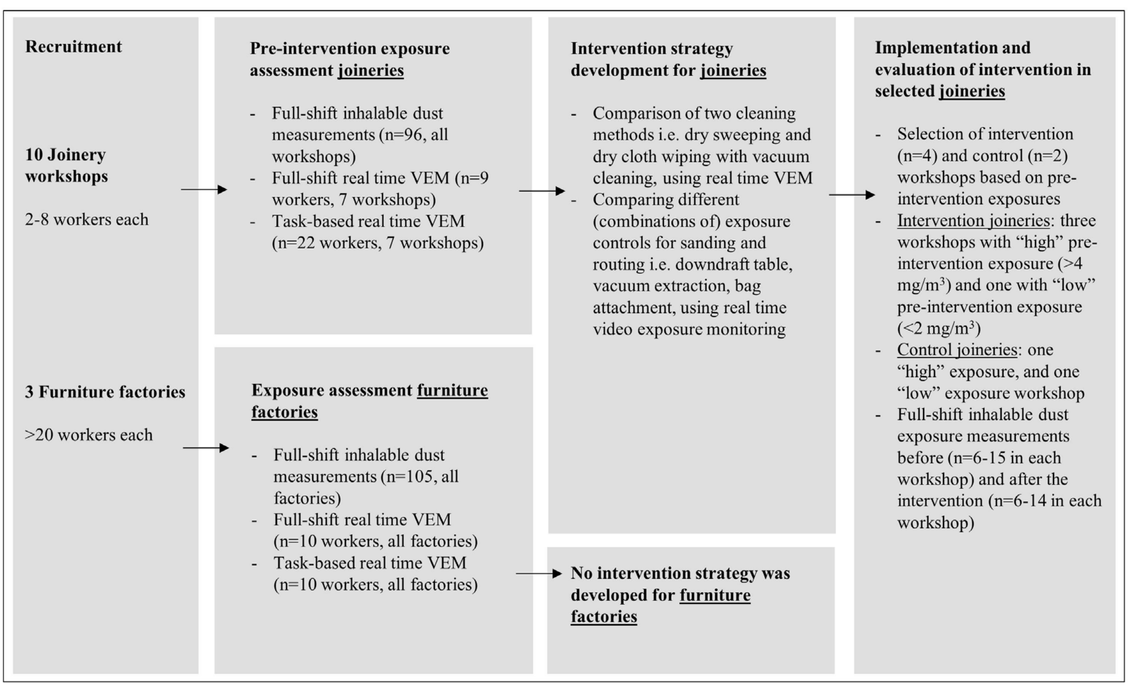

Figure 1. Study design.

Table 1. Pre-intervention inhalable dust 8-TWA exposure measurements.

	Number of employees	*N*	GM (GSD) mg m^{-3}	Minimum–maximum	% above 1 mg m^{-3}
Joineries					
A	8	15	5.7 (2.6)	1.9–48.4	100%
B	3	6	1.7 (1.8)	0.7–3.3	83.3%
C	5	8	1.6 (2.2)	0.7–5.0	62.5%
D	2	7	4.9 (2.1)	1.6–17.5	100.0%
E	3	6	6.2 (1.6)	3.5–14.1	100.0%
F	7	12	4.2 (1.5)	1.1–7.8	100.0%
G	3	8	1.1 (2.1)	0.5–4.3	37.5%
H	7	18	1.7 (1.6)	0.9–3.7	77.8%
I	4	15	1.6 (2.3)	0.4–9.0	80.0%
J	8	1	9.5 (—)	—	100%
Joineries combined	50	96	2.5 (2.5)	0.4–48.4	83.3%
Furniture factories					
K	>20	46	0.5 (2.7)	0.1–9.3	17.4%
L	>20	28	0.8 (1.9)	0.3–5.6	28.6%
M	>20	31	0.6 (1.8)	0.2–3.1	12.9%
Furniture factories combined	>60	105	0.6 (2.3)	0.1–9.3	19.0%

Full-shift 8-h TWA exposure measurements

In total, 201 personal inhalable dust samples across the 10 joineries and 3 furniture-making factories were collected. Similar to previous studies measuring wood dust (Douwes *et al.*, 2006; Spee *et al.*, 2007), we used pumps set at a flow rate of 2.0 (±0.1) l min^{-1} with inhalable PAS-6 dust sampling heads containing 25-mm Whatman glass fibre filters with a nominal pore size of 5 µm. Filters were weighed prior and after sampling using a Mettler Toledo AX105 microbalance with a resolution of 1 µg. Dust concentrations (in mg m^{-3}) were adjusted for field blanks (n = 32) resulting in one sample with a dust level below the detection limit; this sample was assigned a value of 0.01 mg m^{-3}. All measurements were taken prior to implementing any intervention measures (see below).

Video exposure monitoring

The VEM system included software developed by VEM Systems LLC and Purdue University (McGlothlin *et al.*, 1996), wireless video cameras to monitor the workers, and Split2 Real-time dust monitors (SKC Inc.) worn by the workers and connected to IOM sampling heads. The Split2 monitors were set at a flow rate of 2.0 ± 0.1 l min^{-1} and inhalable dust concentrations were recorded every second and sent wirelessly to a computer. Calibration of the Split2 monitor was conducted prior to each recording session. Full-shift VEM measurements in 19 randomly selected workers from 7 joineries and 3 furniture factories were conducted to obtain information on tasks and exposures representative of typical working days. We subsequently conducted further task-based measurements in 32 workers from the same 7 joineries and 3 furniture factories covering the following tasks: assembly, biscuit cutting, buzzing (using an underhand table planer), computer numerical control (CNC) routing, cleaning, edge banding, hand sanding, machine belt sanding, gluing, mortising (to cut square or rectangular holes in timber to create joints), planing, orbital sanding, band sawing, mitre sawing, routing, rip sawing, table sawing, traditional hand sawing, spindle moulding/wood shaping, tenoning (to create joints), thicknessing (using a thickness planer), and other miscellaneous tasks. All VEM measurements were taken prior to implementing any intervention measures (see below).

Intervention strategy development

Based on the results of previous studies (Hampl and Johnston, 1985; Thorpe and Brown, 1994; Scheeper *et al.*, 1995; Martin and Zalk, 1997; Brosseau *et al.*, 2001; Lazovich *et al.*, 2002; Rongo *et al.*, 2002; Schlunssen *et al.*, 2008) and our own VEM measurements (see Results section), intervention experiments were developed focussing on improved cleaning methods (all workshops used dry sweeping and dry cloth wiping) and hand-tool-specific exposure control measures (most workers used no control measures or only a simple bag attachment). Cleaning experiments were conducted in one of the participating workshops and involved comparing two cleaning methods on two occasions. The first session involved field staff-performing dry sweeping and dry cloth wiping in one half of the shop for 37 min (without workers present). The next day, the same field staff cleaned the other half of the shop (also with no workers present) with a vacuum cleaner for 44 min. The effects on exposure levels were evaluated using VEM.

Exposure control measures for sanding and routing were tested in an experimental workshop set-up in our laboratory. These involved testing the following controls: downdraft table, vacuum extraction attached to sander or router, bag attached to sander (no bag attachment was available for the router), downdraft table with vacuum extraction, and downdraft table with bag attached to sander. Sanding experiments involved sanding drawers [medium density fibreboard (MDF), 840 mm × 400 mm × 150 mm] using an orbital sander (Bosch GEX 125-1 A/AE random orbital sander) with 180 grit sandpaper for 15 min per control option at a steady pace. Between experiments, wood dust was removed from equipment and surrounding surfaces to minimize cross contamination. All measurements were repeated six times (or in case of vacuum extraction seven times). For routing, we used a plunge router (Bosch POF 1200 AE router) with a router bit to cut 5-mm width and 5-mm deep. For each control method, 10 lines (between 700 and 800 mm) were routed across the surface of MDF boards at a steady pace. Each control option was repeated four times. Vacuum extraction was applied by using a vacuum cleaner (Arges Vacuum Cleaner 100W 30L) which had 23 kPa (23.13 cfm) of suction and was attached to the orbital sander and router. The bag attached to the sander was a box attachment, which had a 'filter microsystem' supplied with the Bosch sander. The downdraft table was custom-made from MDF (1000 mm × 1000 mm × 150 mm) with the surface area (980 mm × 970 mm × 5 mm) containing holes of 18 mm in diameter, and spaced 54 mm between them. The downdraft table had a 110-mm diameter hole, which was connected to a dust collector (ToolShed Trade Dust Extractor 2HP), which had an air flow of 1500 cfm. The effects on exposure levels were evaluated using VEM.

Implementation and evaluation of intervention

Four joineries were selected based on whether they were agreeable to applying specific intervention measures and on pre-intervention exposure levels measured in the survey, i.e. three 'high' exposure (>4 mg m^{-3}) and one 'low' exposure (<2 mg m^{-3}) workshop. We also included one 'high' exposure and one 'low' exposure control workshop where no intervention measures were introduced. Due to the nature of the intervention, workshops and participants were not blinded to intervention status. A total of 29 workers were involved in this part of the study.

The control methods, which in our experiments were shown to be most effective, were used for the intervention that entailed cleaning with a vacuum cleaner (Festool CT26E), and using orbital sanders and handheld routers (Festool) with vacuum extraction combined with the use of a downdraft table. The downdraft tables were connected to dust collectors provided by the researchers or to existing local exhaust ventilation. Throughout the intervention period, workers were actively encouraged to use the control options provided. In each of the six participating workshops, 6–15 full-shift personal inhalable dust samples were collected prior to and 6–14 following the intervention. Sampling took place over a period of 8 months, i.e. 4 months prior and 4 months following the intervention.

Statistical analyses

All analyses were conducted using SAS (SAS Institute Inc. 2011, Base SAS 9.3 Procedures Guide Cary, NC, USA). As dust exposure approximated a log-normal distribution, all exposure data were logarithmically transformed and presented as geometric means (GM) with geometric standard deviations (GSD).

Full-shift VEM data, involving exposure data recorded every second, was linked by the fieldworker, through an option in the VEM software, to specific tasks and activities undertaken by the participant, and types of materials and exposure control used while conducting these tasks. All VEM footage was subsequently evaluated in the laboratory and linkage with task, activities and materials used checked for accuracy, and if required, corrections were made. The same was done for task-specific VEM measurements. Lag time associated with air passing through the tubing prior to it reaching the measuring unit is minimal and was therefore not taken into account. Combined (i.e. full-shift VEM and task-based VEM), this resulted in tens-of-thousands linked exposure observations, which allowed detailed analyses of exposure determinants.

We used generalized linear mixed models (GLMM), separately for joiners and furniture makers, with a random intercept for each worker, thus taking into account repeat measures in the same workers. Autocorrelation between measurements was taken into account by specifying a first order autoregressive structure for the residual covariance matrix. Log-transformed exposure data were used as the dependent variable with the independent (fixed effects) variables including specific tasks and activities, types of materials used, and type of control measure used. The use of a first-order autoregressive covariance structure combined with the large number of individual data points resulted in analyses exceeding computer-processing capacity. To deal with this, we restricted the VEM analyses to include 'only' one in 10 observations for joiners and one in 5 observation in furniture workers, equalling the maximum data points that we were able to use without exceeding computing capacity (i.e. we used exposure measurements taken every 10 or 5 s rather than every 1 s). To validate the results, we repeated the analyses using subsequent sets of 10- or 5-s measurements, which showed highly comparable results (data not shown) indicating that results were robust. Since we used log-transformed exposure, data the outcomes of the GLMM are expressed as exposure ratios (with 95% confidence limits). The reference categories were chosen to represent tasks/activities and materials associated with the lowest exposure in each of the two industries; for type of control the reference category was 'no control' for both industries.

Due to significant collinearity between tasks and some materials used in furniture workers, we were not able to assess the impact of the use of specific wood products on exposure. As a consequence, for these analyses, we combined the materials 'laminated MDF', 'MDF', and 'particle board' into an aggregated materials group referred to as 'wood-based materials'. Also, 13 workers in the furniture-manufacturing industry were not actively involved in the furniture production making process itself (as also reflected by the fact that they did not process wood-based or other materials). These workers conducted other tasks including management, logistics, and cleaning. Attempts to include exposure data of these workers in the GLMM analyses resulted in significant collinearity, which could only be resolved by excluding the data for these workers from the GLMM analyses.

For comparing dust exposures associated with different intervention strategies tested under laboratory conditions, we used GLMM with log-transformed exposure data as the dependent variable and the intervention(s) as the independent [fixed effect(s)] variable(s). We used 'no control' as the reference category. To assess the effect of interventions implemented in three 'high' and one 'low' exposure joinery workshops (and one high and low control workshop), we initially compared pre- and post-intervention exposures using GLMM with the pre-intervention situation chosen as the reference category. Comparisons were made for each workshop separately. We subsequently used GLMM to compare exposures between intervention and control workshops with pre/post exposure and control/intervention entered as fixed effects and worker as a random intercept. Due to log-transformed exposure data the outcomes of the regression analyses are expressed as exposure ratios (with 95% confidence limits) and presented (for clarity) as the percentage difference, i.e. (exposure ratio − 1) × 100%, between post- and pre-intervention exposures and intervention and control workshops.

Results

Exposure levels

Personal inhalable dust exposure in joinery workers was relatively high (GM 2.5 mg m^{-3}, GSD 2.5), with 83% of workers exposed to levels exceeding the occupational exposure limit of 1 mg m^{-3} recommended by the American Conference of Governmental Industrial Hygienists (ACGIH, 2016; Table 1), and 56% exceeding the current New Zealand workplace exposure limit for soft wood of 2 mg m^{-3} (Worksafe New Zealand, 2016). Exposure levels for furniture makers were considerably lower (GM 0.6, GSD 2.3), but 19% of the measurements nonetheless involved levels exceeding the ACGIH (2016) threshold limit values (TLV) with 7% exceeding the New Zealand workplace exposure limit.

Exposure determinants

Joinery workers spent on average almost 60% of their work shift conducting assembly work (21.5%); miscellaneous activities such as drawing plans, finding materials and tools, and talking to clients, (27.3%); and computer CNC routing (12.1%) (Table 2). A relatively large proportion of their time is also spent on conducting tasks using hand tools, i.e. routing (6.5%) and sanding using a belt sander (9%) or orbital sander (1.4%). Other common activities include sanding by hand (5.3%) and using a table saw (4.2%). Workers in furniture factories spent a large proportion of time on CNC routing (77.6%), reflecting the high degree of automation in this industry. The remainder is spent on assembly (16.9%), edge banding (4.2%), routing using a handheld device (1.1%), and sawing (0.1%).

For joiners, cleaning was associated with 3-fold higher ($P < 0.001$) dust concentrations, compared to gluing (which was chosen as the reference category; Table 2). In the same group, the use of hand tools (orbital and band sanding, planing, and routing) showed 3.0 (routing) to 11.0 (planing) fold higher dust exposures, and hand sawing and hand sanding were associated with

Table 2. Exposure determinants expressed as exposure ratios and task duration in percentages for joiners and furniture makers.

Determinants	Joiners			Furniture manufacturers		
	Number of 1-s VEM observations	% time allocated to task[a]	Exposure ratio (95% CL)[b]	Number of 1-s VEM observations	% time allocated to task[a]	Exposure ratio (95% CL)[c]
Tasks/activities						
Miscellaneous	53 176	27.3%	1.7 (1.1–2.6)*	3532	0.0%	2.4 (1.1–5.5)*
Cleaning	1824	0.7%	3.0 (1.9–4.9)***	—	—	
CNC	13 267	12.1%	2.4 (1.5–4.0)***	110 694	77.6%	2.2 (1.0–4.9)
Biscuit cutting	727	0.2%	2.5 (1.5–42)***	—	—	—
Tenoning	1703	1.1%	3.9 (2.3–6.5)***	—	—	—
Mortising	1421	0.5%	2.5 (1.5–4.2)***	—	—	—
Routing	6724	6.5%	3.0 (2.0–4.5)***	824	1.1%	1.1 (0.9–1.2)
Spindle moulder	6674	4.6%	2.4 (1.6–3.8)***	—	—	—
Sanding (hand)	19 584	5.3%	3.4 (2.3–5.1)***	11	0.0%	1.8 (1.0–3.5)
Sanding (handheld orbital)	8320	1.4%	4.0 (2.6–6.1)***	—	—	—
Sanding (machine belt sander)	11 648	9.0%	3.9 (2.5–6.1)***	—	—	—
Edge banding	3784	1.2%	1.1 (0.7–1.8)	4720	4.2%	1.4 (1.2–1.7)***
Buzzing (underhand table planer)	589	0.6%	1.5 (0.8–2.8)	—	—	—
Thicknessing (overhead planer)	1561	0.6%	1.4 (0.8–2.5)	—	—	—
Planing (traditional)	1076	0.5%	2.0 (1.2–3.2)**	—	—	—
Planing (electric handheld)	2273	0.4%	11.0 (7.0–17.4)***	—	—	—
Sawing (band saw)	1591	1.2%	2.4 (1.4–4.1)**	—	—	—
Sawing (mitre saw)	1658	0.6%	2.9 (1.9–4.4)***	—	—	—
Sawing (rip saw)	30	0.1%	2.9 (1.0–8.3)*	—	—	—
Sawing (hand saw)	239	0.2%	3.0 (1.5–6.1)**	—	—	—
Sawing (table/circular saw)	14 866	4.2%	2.2 (1.4–3.4)***	114	0.1%	5.4 (2.1–13.9)***
Assembly	34 579	21.5%	2.2 (1.5–3.3)***	17 209	16.9%	Reference
Gluing	796	0.2%	Reference	—	—	—
Materials used				—	—	—
Laminated MDF	33 272	—	1.3 (1.1–1.4)***	—	—	—
MDF	13 137	—	0.9 (0.8–1.1)	—	—	—
Particle board	—	—	—	—	—	—
Plywood	26 940	—	1.2 (1.0–1.4)*	—	—	—
Wood-based materials[d]	—	—	—	132 810		Reference
Other (metal, plastic, etc.)	—	—	—	4294	—	2.0 (1.6–2.6)***

Table 2. *Continued*

Determinants	Joiners			Furniture manufacturers		
	Number of 1-s VEM observations	% time allocated to task[a]	Exposure ratio (95% CL)[b]	Number of 1-s VEM observations	% time allocated to task[a]	Exposure ratio (95% CL)[c]
None	57053	—	1.3 (1.0–1.6)	—	—	—
Timber	57708	—	Reference		—	—
Control measure						
Local exhaust ventilation	49778	—	1.1 (0.9–1.4)	112570	—	1.1 (0.7–1.8)
Extraction to bag	11333	—	1.2 (1.0–1.5)		—	—
Other	518	—	0.7 (0.4–1.2)		—	—
None	126481	—	Reference	42444	—	Reference

Random intercepts for individual workers were included in the analyses (GLMM): [a]based on the full-shift measurements; [b]based on the analyses including 1 of every 10 measurements; variance between workers = 0.44, variance within worker = 0.95; autoregression correlation coefficient = 0.77; [c]based on the analyses including 1 of every 5 measurements; variance between workers = 0.42, variance within worker = 0.40; autoregression correlation coefficient = 0.92; [d]wood-based materials refer to an aggregate of 'laminated MDF', 'MDF', and 'particle board'. CL, confidence limit.

$^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

3.0- to 3.4-fold higher ($P < 0.01$) exposures. The highest exposures for furniture makers were associated with sawing using a table saw/circular saw (5.4-fold higher; $P < 0.001$) and miscellaneous tasks (2.4-fold higher; $P < 0.05$) not further specified. Higher dust exposures were also found for CNC work (2.2-fold; borderline statistically significant, $P < 0.1$) and edge banding (1.4-fold; $P < 0.001$). Working with plywood or laminated MDF in joinery workshops was associated with higher exposures of 20–30% ($P < 0.05$) compared to working with timber, while in furniture factories the highest exposures were associated with the use of other non-wood-based materials ($P < 0.001$). Control measures such as local exhaust ventilation and bag extraction systems were not significantly associated with dust exposures (Table 2).

Intervention strategy development

The cleaning experiment showed that average dust concentrations were 10 times lower ($P < 0.001$) when using a vacuum cleaner (range 0.0–4.57 mg m^{-3}; GM 0.35 mg m^{-3}) compared to dry wiping and dry sweeping (range 0.0–24.0 mg m^{-3}; GM 3.56 mg m^{-3}) (Fig. 2).

The orbital sander experiments showed a small reduction in inhalable dust exposure of 8.3% [non-significant (NS)] for the use of the downdraft table. Vacuum extraction resulted in a 75.0% reduction of exposure ($P < 0.001$; Table 3), and a further reduction was achieved by combining it with the use of a downdraft table resulting in an overall reduction in dust emissions of 85.5% ($P < 0.001$). Interventions with a bag attachment resulted in higher dust emissions, i.e. an increase of 73.6% ($P < 0.1$). Closer examination of the VEM footage and additional observations during the experimental trials suggest that this was not based on outliers and/or technical problems.

The router experiments showed that using vacuum extraction on its own reduced the dust levels by 27.6% (NS), whereas when using vacuum extraction in combination with the downdraft table, a reduction of 42.5% was achieved, with the latter being borderline statistically significant ($P < 0.10$; Table 3). Using a downdraft table on its own resulted in no reduction of exposure.

Intervention effectiveness evaluation

When comparing pre- and post-intervention personal exposures for each workshop separately, we found that two workshops with high baseline exposures (>4 mg m^{-3}) showed a significant decrease following the intervention of 54 and 68%, respectively ($P < 0.05$), and the other high exposure workshop also showed a reduction of 11%, but this did not reach statistical significance (Table 4). Expo-

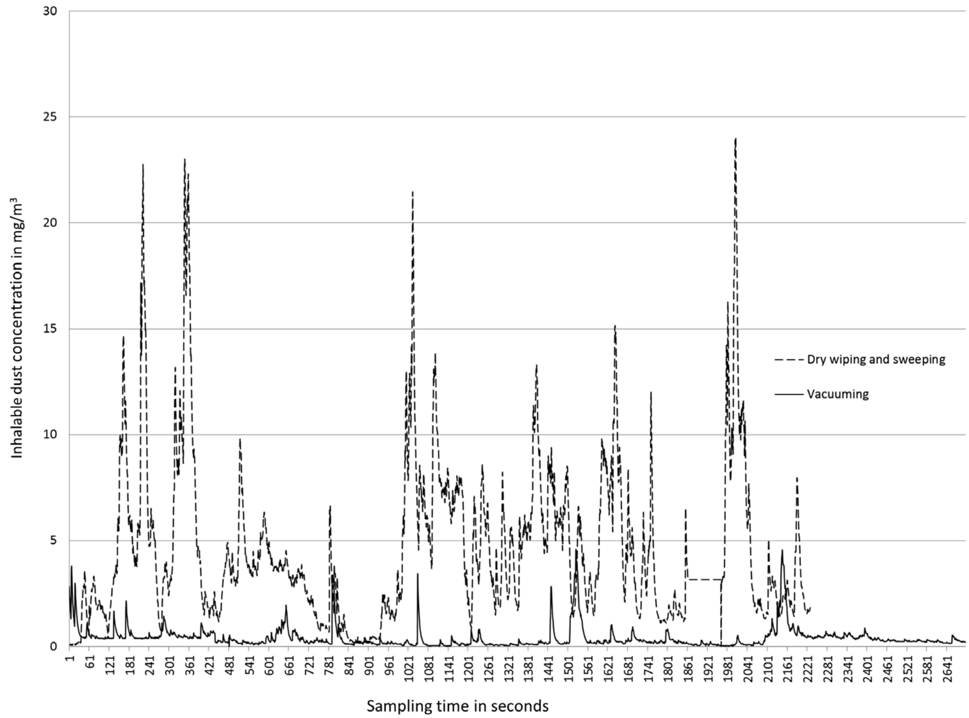

Figure 2. Inhalable dust concentrations (mg m^{-3}) measured when dry wiping and sweeping (dashed line) versus dust concentrations measured when using a vacuum cleaner (solid line).

sure in the 'control' workshop with high baseline exposure was reduced by 35%, but this was not statistically significant. The 'low' exposure workshop and 'low' exposure control both showed reduced exposures following the intervention period (9 and 22%, respectively), but these reductions were not statistically significant. When mixed model analyses were applied taking into account both pre/post differences and differences between intervention and control workshops, we found an overall (borderline statistically significant, $P < 0.10$) reduction in dust exposures of 30% following intervention, but only in those workshops with high baseline exposures. No intervention effect was found in the low exposure workshop (Table 4).

Discussion

Our pre-intervention cross-sectional study showed that exposure to wood dust was high in joinery workers. In furniture factories, exposures were considerably lower. The use of hand tools significantly increased dust levels, with the greatest increases observed in joinery workers. Cleaning (sweeping and dry wiping) was also associated with high dust exposures in joinery workers. Experiments under 'laboratory' conditions showed that local vacuum extraction combined with the use of a downdraft table, and using a vacuum cleaner for cleaning reduced dust emissions considerably. When these interventions were applied in joinery workshops, a borderline statistically significant ($P < 0.10$) reduction in exposure of 30% was found in workshops with 'high' baseline exposures and no reduction was shown in the workshop with 'low' baseline exposures when compared to control workshops in which no intervention took place.

Our results are consistent with previous studies showing that dry wiping and dry sweeping are significant determinants of dust exposure in the wood conversion industry (Brosseau *et al.*, 2001; Rongo *et al.*, 2002; Schlunssen *et al.*, 2008) and that the use of vacuum cleaners can significantly reduce airborne exposures as demonstrated in other occupational and environmental settings (Ettinger *et al.*, 2002; Skulberg *et al.*, 2004). Similarly, like the current study, previous studies have found that local vacuum extraction for hand tools significantly reduces wood dust emissions (Thorpe and Brown, 1994; Brosseau *et al.*, 2001). However, attempts to apply cost-effective interventions outside the laboratory have generally not been successful with only marginal reductions in wood dust exposures achieved (Lazovich *et al.*, 2002). In the current study, we found an overall borderline statistically significant reduc-

Table 3. Sander and router dust control experiments.

Experiment	Emission (mg m^{-3})		
	N	GM (GSD)	% difference (95% CL)
Sander			
No controls	6	0.8 (1.2)	—
Downdraft table	6	0.8 (1.2)	−8.3 (−46.2; 56.5)
Vacuum extraction	7	0.2 (1.2)	−75.0 (−85.1; −58.2)***
Bag attachment	6	1.5 (1.2)	73.6 (−0.9; 204.0)#
Downdraft + vacuum extraction	6	0.1 (1.2)	−83.5 (−90.3; −71.9)***
Downdraft + bag attachment	6	0.8 (1.2)	−3.4 (−44.8; 69.2)
Router			
No controls	4	0.6 (1.2)	—
Downdraft table	4	0.8 (1.2)	34.2 (−29.5; 155.5)
Vacuum extraction	4	0.4 (1.2)	−27.6 (−62.0; 37.7)
Downdraft + vacuum extraction	4	0.3 (1.2)	−42.5 (−69.8, 9.4)#

CL, confidence limit.
#$P < 0.10$; ***$P < 0.001$.

tion of 30% in wood dust exposure (after taking into account changes in exposures in the control workshop; see below) associated with improved cleaning and local exhaust ventilation on hand tools, but only in workshops characterized as 'high' exposed at baseline. No significant differences were found in the 'low' exposure workshop (which had a baseline GM exposure level of 1.6 mg m^{-3}) suggesting that reducing exposure to levels below current international exposure standards (i.e. <1 mg m^{-3}) requires a more comprehensive approach than the currently tested intervention, as has also previously been suggested (Martin and Zalk, 1997). In particular, in the current study, vacuum extraction was employed only on routers and sanders as other tools would have required modifications to the hardware to make them compatible with the ducting fitted to the dust extractor. As confirmed by VEM (Table 2), these other tools also represent important sources of exposures and connecting all machines/tools to local exhaust extraction systems (which were present in most workshops, but typically not connected to all dust generating devices) would have likely reduced exposure levels more. Although the modifications required to making all tools/machines compatible are relatively easy, this was not practicable in the current study.

We also showed a reduction in exposure levels in workshops in which no intervention measures were implemented. Reduced exposure levels in control workshops may be due to changes in production volume between the pre- and post-intervention period, which we were unable to control for in the analyses. However, personal communication with workshop owners suggested that this was not the case, but detailed information to confirm this was not available. The baseline exposure survey could have acted as an intervention resulting in lower dust exposures in control workshops, but we did not report back results of the measurements until after study completion suggesting that this is an unlikely explanation. Nonetheless, it cannot be excluded that our presence pre- and post-intervention in control shops may have contributed to unintended behavioral changes resulting in lower exposures. Also, of the 28 workers involved in pre- and post-intervention exposure measurements, 18 were measured both before and after intervention whereas 11 workers were measured only prior or only following intervention. Differences between workers may therefore have contributed to some of the differences observed. However, work activities and level of skill for those who participated only before or only after intervention were highly comparable, and between-worker exposure variance was relatively low compared to within-worker variance (Table 2) suggesting that any potential effect would be small. Finally, seasonal effects may have played a role, but our baseline exposure data did not show seasonal variation (data not shown), suggesting that seasonal effects, if present, were small. Also, we were advised by management that, with exception of the period around Christmas (during which period we did not conduct exposure measurements), production was similar across seasons. We therefore do not believe that seasonable effects have materially contributed to effects observed in this study.

Table 4. Pre- and post-intervention exposures and differences (expressed as percentage difference) in four joinery workshops and two control workshops.

	Pre-intervention exposure (mg m^{-3})		Post-intervention exposure (mg m^{-3})		Post- and pre-intervention difference[b]	Difference between intervention and control[c]
Joineries (*N* workers)[a]	*N*	GM (GSD)	*N*	GM (GSD)	% difference (95% CL)	% difference (95% CL)
Low baseline exposure						4 (−41; 82)
B—Control (2)	6	1.7 (1.8)	6	1.3 (2.4)	−22 (−70; 104)	
C—Intervention (4)	8	1.6 (2.1)	14	1.5 (2.2)	−9 (−56; 88)	
High baseline exposure						−30 (−55; 8)[#]
A—Control (8)	15	5.7 (2.6)	14	3.8 (2.4)	−35 (−68; 33)	
D—Intervention (3)	7	4.9 (2.1)	6	2.4 (2.6)	−11 (−74; 212)	
E—Intervention (4)	6	6.2 (1.6)	6	2.4 (2.1)	−68 (−88; −13)*	
F—Intervention (8)	12	4.2 (1.5)	8	1.9 (2.0)	−54 (−72; −22)**	

[a]Of the 28 workers involved in pre- and post-intervention exposure measurements, 18 were measured both before and after intervention. Six workers were measured only before and 5 workers were measured only after the intervention.
[b]Comparing pre- and post-intervention exposure levels in each workshop separately (using GLMM).
[c]Comparing pre- and post-intervention exposure differences between intervention and control workshops, but stratified by high and low baseline exposure (using GLMM).
[#]$P < 0.10$; *$P < 0.05$; **$P < 0.01$.

The experiments testing the efficacy of several intervention options showed that the use of a filter bag attachment to hand tools, as is commonly used by most joiners and furniture makers (as well as many other workers using hand tools), was ineffective in reducing emissions to inhalable particles (i.e. the use of interventions with a filter bag resulted in higher dust emissions rather than lower; Table 3). This is of concern given the widespread use and the false sense of protection it may offer workers, shop owners, and managers. We have only tested one filter bag attachment, but initial measurements using another filter bag showed similar results (data not shown). It is therefore possible that other commonly used bags/cartridges are equally ineffective, although previous international studies suggest that there may be some benefit in using these devices (Thorpe and Brown, 1994).

In contrast to some previous studies that showed high wood dust exposure levels in furniture factory workers (Scheeper *et al.*, 1995), our study showed relatively low exposure levels in these workers. This could be due to differences between furniture factories and the activities undertaken by the workers. In particular, in our study workers spent very little time sanding (Table 2), which has previously been shown to be a significant contributor to furniture workers' overall wood dust exposure (Scheeper *et al.*, 1995). Alternatively, the lower exposures may be due to progress made in occupational hygiene and improved exposure controls in recent times. The 'within-worker exposure variance' in furniture manufacturing was also lower than that observed in joinery workers (0.40 versus 0.95; Table 2). This most likely reflects the differences in work processes between both industries in New Zealand, with a more controlled work environment and more standardized production methods, and a greater degree of specialization of individual work activities in the furniture-making industry, compared to joinery workshops.

This study had several limitations. For furniture workers, we observed collinearity between some tasks and different materials used, and the inclusion of 13 workers who were not actively involved in the furniture-manufacturing process itself resulted in further collinearity. We dealt with this by creating an aggregate 'wood-based materials' group and omitting exposure data from those 13 workers. This may have affected the results; however, analyses including data from the 13 workers did not appreciably affect the estimated exposure ratios for specific tasks/activities. Including all materials in the analyses (rather than using an aggregate 'wood-based materials' group) also did not affect the exposure ratios for specific tasks/activities suggesting that results were robust. As noted above, not all hand tools used by the workers during the intervention period were connected to a vacuum extraction system. Similarly, in many workshops, static (non-handheld) power tools known to significantly contribute to peak personal exposures (Table 2) were not always connected to local exhaust ventilation, and the intervention package did not address this. Therefore, the estimated reduction in exposure that can be achieved in high exposure workshops may be an underestimation of what could be achieved if adequate exhaust ventilation was employed on all power tools including non-handheld tools. Another limitation is the relatively small sample of workshops in which the interventions were implemented. This is particularly an issue in an industry where production volumes and intensity are variable over time as is the case for many joiners and, to a lesser extent, furniture makers. As noted above, we were not able to directly account for differences in production volumes pre- and post-intervention leaving some uncertainty about the actual magnitude of the achievable reductions in exposure. Also, our intervention results apply only to joineries, which were prioritized over furniture shops based on higher baseline exposures. Furthermore, although we had detailed information on personal exposures and job tasks in real time (using VEM), it did not take into account secondary sources (i.e. exposures related to work activities conducted by colleagues and/or re-suspension of surface dust left from previous tasks) and/or specific worker behaviours. We also grouped several activities together and labelled them as 'miscellaneous', which may have resulted in missing some activities associated with high peak exposures. This is particularly relevant for furniture makers for whom miscellaneous tasks were associated with a 2.4-fold increase in exposures (Table 2). However, upon re-examination of the VEM material, we were not able to define specific tasks associated with these increased exposure levels, which appeared to be associated with re-suspension of surface dust emphasizing the importance of good housekeeping.

In conclusion, this study has shown that wood dust exposures are high in joinery workers and (to a lesser extent) furniture makers. The use of hand tools and conventional cleaning methods (dry wiping and sweeping) significantly contributed to high exposures in joinery workers, while use of vacuum extraction on hand tools and alternative cleaning methods were shown to have the potential to significantly reduce dust exposures. Applying these measures in joinery workshops is feasible and is likely to significantly reduce workplace exposures. Finally, using VEM as a tool to better understand the impact of engineering controls and best work practices for controlling wood dust showed considerable promise in this study.

Acknowledgements

This study was funded by the Department of Labour (now WorkSafe New Zealand) and the New Zealand Health Research Council. The Centre for Public Health Research is funded through a Health Research Council Programme Grant. We are grateful for the assistance provided by Prof. Bill Glass and a team of students—Grace Chen, Sam Keer, and Helene Marsters—who conducted the cleaning intervention experiments and Koon Ching Wong for assisting with the statistical analyses. We also thank Festool for the loan of routers and orbital sanders and the shop owners/managers, joiners, and furniture makers who participated in this study. Also, we thank VEM Systems, LLC., and Purdue University for the use of their VEM patented data collection system.

Declaration

The authors declare no conflict of interest relating to the material presented in this article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

References

American Conference of Governmental Industrial Hygienists (ACGIH). (2016) *Threshold limit values for chemical substances and physical agents & biological exposure indices*. Cincinnati, OH: ACGIH.

Barcenas CH, Delclos GL, El-Zein R *et al*. (2005) Wood dust exposure and the association with lung cancer risk. *Am J Ind Med*; **47**: 349–57.

Bohadana, AB, Massin N, Wild P *et al*. (2000) Symptoms, airway responsiveness, and exposure to dust in beech and oak wood workers. *Occup Environ Med*; **57**: 268–73.

Borm PJ, Jetten M, Hidayat S *et al*. (2002) Respiratory symptoms, lung function, and nasal cellularity in Indonesian wood workers: a dose-response analysis. *Occup Environ Med*; **59**: 338–44.

Brosseau LM, Parker DL, Lazovich D *et al*. (2001) Inhalable dust exposures, tasks, and use of ventilation in small woodworking shops: a pilot study. *AIHAJ*; **62**: 322–9.

Brosseau LM, Parker DL, Lazovich D *et al*. (2002) Designing intervention effectiveness studies for occupational health and safety: The Minnesota Wood Dust Study. *Am J Ind Med*; **41**: 54–61.

Demers PA, Kogevinas M, Boffetta P *et al*. (1995) Wood dust and sino-nasal cancer: pooled reanalysis of twelve case-control studies. *Am J Ind Med*; **28**: 151–66.

Douwes J, McLean D, Slater T *et al*. (2001) Asthma and other respiratory symptoms in New Zealand pine processing sawmill workers. *Am J Ind Med*; **39**: 608–15.

Douwes J, McLean D, Slater T *et al*. (2006) Pine dust, atopy and lung function: a cross-sectional study in New Zealand sawmill workers. *Eur Resp J*; **28**: 791–8.

Ettinger AS, Bornschein RL, Farfel M *et al*. (2002) Assessment of cleaning to control lead dust in homes of children with moderate lead poisoning: treatment of lead-exposed children trial. *Environ Health Perspect*; **110**: A773–9.

Hampl V, Johnston OE. (1985) Control of wood dust from horizontal belt sanding. *Am Ind Hyg Assoc J*; **46**: 567–77.

IARC. (1995) Wood dust and formaldehyde. In Monographs on the evaluation of the carcinogenetic risk of chemicals to humans. IARC Monograph No. 62. Lyon, France: IARC Press.

Jacobsen G, Schlünssen V, Schaumburg I *et al.* (2008) Longitudinal lung function decline and wood dust exposure in the furniture industry. *Eur Respir J*; **31**: 334–42.

Jayaprakash V, Natarajan KK, Moysich KB *et al.* (2008) Wood dust exposure and the risk of upper aero-digestive and respiratory cancers in males. *Occup Environ Med*; **65**: 647–54.

Kauppinen T, Vincent R, Liukkonen T *et al.* (2006) Occupational exposure to inhalable wood dust in the member states of the European Union. *Ann Occup Hyg*; **50**: 549–61.

Lazovich D, Murray DM, Brosseau LM *et al.* (2002) Sample size considerations for studies of intervention efficacy in the occupational setting. *Ann Occup Hyg*; **46**: 219–27.

Martin JR, Zalk DM. (1997). Carpenter shop wood dust control: practical experience to reduce hardwood dust exposures below the American Conference of Governmental Industrial Hygienists Threshold Limit Values. *Appl Occup Environ Hyg*; **12**: 595–603.

McGlothlin JD, Gressel MG, Hertbrink WA *et al.* (1996) Real-time exposure assessment and job analysis techniques to solve hazardous workplace exposures. In Bhattacharya A, McGlothlin JD, editors. *Occupational ergonomics: theory and applications*. New York, NY: Marshal Dekker Inc.

Rongo LMB, Besselink A, Douwes J *et al.* (2002) Respiratory symptoms among woodworkers in small-scale workshops in Dar es Salam, Tanzania. *J Occup Environ Med*; **44**: 1153–60.

Rosén G, Andersson IM, Walsh PT *et al.* (2005) A review of video exposure monitoring as an occupational hygiene tool. *Ann Occup Hyg*; **49**: 201–17.

Scheeper B, Kromhout H, Boleij JS. (1995) Wood-dust exposure during wood-working processes. *Ann Occup Hyg*; **39**: 141–54.

Schlunssen V, Jacobsen G, Erlandsen M *et al.* (2008) Determinants of wood dust exposure in the Danish furniture industry – results from two cross-sectional studies 6 years apart. *Ann Occup Hyg*; **52**: 227–38.

Schlunssen V, Schaumburg I, Taudorf E *et al.* (2002) Respiratory symptoms and lung function among Danish woodworkers. *J Occup Environ Med*; **44**: 82–98.

Schlunssen V, Sigsgaard T, Schaumburg I *et al.* (2004) Cross-shift changes in FEV1 in relation to wood dust exposure: the implications of different exposure assessment methods. *Occup Environ Med*; **61**: 824–30.

Shamssain MH. (1992) Pulmonary function and symptoms in workers exposed to wood dust. *Thorax*; **47**: 84–7.

Skulberg KR, Skyberg K, Kruse K *et al.* (2004) The effect of cleaning on dust and the health of office workers: an intervention study. *Epidemiology*; **15**: 71–8.

Spee T, van de rijdt-van Hoof E, van Hoof W *et al.* (2007) Exposure to wood dust among carpenters in the construction industry in the Netherlands. *Ann Occup Hyg*; **51**: 241–8.

Talini D, Monteverdi A, Benvenuti A *et al.* (1998) Asthma-like symptoms, atopy, and bronchial responsiveness in furniture workers. *Occup Environ Med*; **55**: 786–91.

Thorpe A, Brown RC. (1994) Measurements of the effectiveness of dust extraction systems of hand sanders used on wood. *Ann Occup Hyg*; **38**: 279–302.

Worksafe New Zealand. (2016) Workplace exposure standards and biological exposure indices. http://www.worksafe.govt.nz/worksafe/information-guidance/all-guidance-items/workplace-exposure-standards-and-biological-exposure-indices/workplace-exposure-standards-and-biological-indices-2016.pdf. Accessed September 2016.