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A Survey of Size-Fractionated Dust Levels in the U.S. Wood Processing Industry

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A survey of size-fractionated dust exposure was carried out in 10 wood processing plants across the United States as part of a 5-year longitudinal respiratory health study. The facilities included a sawmill, plywood assembly plants, secondary wood milling operations, and factories producing finished wood products such as wood furniture and cabinets. Size-fractionated dust exposures were determined using the RespiCon Personal Particle Sampler. There were 2430 valid sets of respirable, thoracic, and inhalable dust samples collected. Overall, geometric mean (geometric standard deviation) exposure levels were found to be 1.44 (2.67), 0.35 (2.65), and 0.18 (2.54) mg/m^3, for the inhalable, thoracic, and respirable fractions, respectively. Averaged across all samples, the respirable fraction accounted for 16.7% of the inhalable dust mass, whereas the corresponding figure for thoracic fraction as a percentage of the inhalable fraction was 28.7%. Exposures in the furniture manufacturing plants were significantly higher than those in sawmill and plywood assembly plants, wood milling plants, and cabinet manufacturing plants, whereas the sawmill and plywood assembly plants exhibited significantly lower dust levels than the other industry segments. Among work activities, cleaning with compressed air and sanding processes produced the highest size-fractionated dust exposures, whereas forklift drivers demonstrated the lowest respirable and inhalable dust fractions and shipping processes produced the lowest thoracic dust fraction. Other common work activities such as sawing, milling, and clamping exhibited intermediate exposure levels, but there were significant differences in relative ranking of these across the various industry segments. Processing of hardwood and mixed woods generally were associated with higher exposures than were softwood and plywood, although these results were confounded with industry segment also.

Keywords milling, RespiCon, sanding, sawing, wood dust

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INTRODUCTION

In 2000, the U.S. Census Bureau reported that more than half a million workers were at risk of exposure to wood dust and its related health effects and injuries nationwide in both primary and secondary wood processing industries as well as in forestry.(1) As of November 2004, the U.S. Department of Labor reported that about 300,000 workers were employed in furniture, cabinetry, pattern and modelmaking, sawing, and woodworking machine industries.(2) Epidemiologic studies show that occupations in the wood processing industry are associated with upper and lower respiratory effects,(3–21) including nasal and sinonasal cancers,(3–9) nasal mucostasis and impaired mucociliary clearance,(10,11) decline of pulmonary function,(12–15) chronic bronchitis, bronchial asthma,(14–19) and organic dust toxic syndrome due to endotoxins and fungi.(20,21)

Wood dust is produced by the shattering of wood cells and the formation of wood chips during sawing, milling, and sanding. Most wood dust particles have an aerodynamic diameter greater than 10 μm and may present in a bimodal size distribution.(22–24) Exposure to wood dust conventionally has been estimated by closed-face cassette sampling for total dust.(25–27) More recently, inhalable dust samplers such as the IOM and Button samplers have become increasingly common for measuring wood processing dust.(28–30) Closed-face cassette sampling for total dust has been shown to underestimate the inhalable fraction present in the dust cloud. As a result, a correction factor is required to convert total dust concentrations into the corresponding inhalable fraction.(31,32)

The wide variety of occupationally associated health effects noted above suggests that size-selective sampling of wood dust is warranted.(22) Recently, the RespiCon, a multistage virtual impactor, has proven to be an effective sampling device for the simultaneous collection of the inhalable, thoracic, and respirable fractions of industrial dust, including that produced during wood processing.[33–37] In addition to the convenience of collecting all three size fractions of dust with one sampling device, the RespiCon simplifies and more accurately characterizes exposure to airborne particles.

This article presents descriptive details of a survey of size-fractionated dust exposure in the U.S. wood processing industry conducted as part of a 5-year longitudinal research study that investigated the relationship between wood dust exposure and respiratory health.[38] Specifically, this survey is based on personal monitoring of dust with the RespiCon sampler at the participating wood processing facilities during the course of the epidemiologic investigation.

MATERIALS AND METHODS

Plants and Participants

There were 10 wood processing plants included in this sampling survey, with primary activities ranging from sawmill operation and plywood assembly to production of finished products such as solid wood furniture and cabinets. Table I shows a listing of the plants, the state in which they were located, and the general type of wood processing operation. Softwoods processed at the various plants included southern yellow pine and Radiata pine. The most common hardwood processed was red oak, with smaller amounts of maple, poplar, birch, rubber tree wood, and cherry. The engineered woods included medium-density fiberboard and particleboard. Plywood (from southern yellow pine) was maintained as a separate category.

During the period from 1999 to 2004, each facility was visited approximately annually, for a total of three or four visits per site. Each sampling visit was approximately 1 week. There were 1–2 shifts sampled daily, with individual sample durations ranging from approximately half the work shift to the entire work shift. The target population included all production workers engaged in activities such as sawing, milling, sanding, assembly, etc., as well as those support personnel who primarily work in dusty areas. Obvious confounding activities, such as metal grinding and welding, were excluded from the sample population. Participation was strictly voluntary. Participants wore the RespiCon personal sampler for periods ranging from almost half a shift to a full shift, as dictated by qualitative assessment of airborne wood dust concentrations. The sampling devices were fixed to the participants with a harness that positions the RespiCon in the breathing zone, at approximately the upper sternum.

Sampling Equipment

Wood dust exposure was determined using the RespiCon Personal Particle Sampler (TSI Inc., Shoreview, Minn.).The RespiCon is a three-stage, virtual impactor that simultaneously collects the respirable, thoracic, and inhalable fractions, as determined by stage-specific cut diameters. Sampling by RespiCon fulfills the ACGIH/ISO/CEN definition criteria for size-selective sampling.[39–41] The inlet head is designed to prevent collection of noninhalable particles ($>100\ \mu$m). The 50% cut size is 4 μm for Stage 1 (respirable) and 10 μm for Stage 2 (tracheo-bronchial). All remaining particles up to the 100-μm inlet head cut diameter are collected on Stage 3 (extrathoracic). Stages 1 and 2 were loaded with either 37-mm glass fiber filters or 2-μm pore size, 37-mm, Teflon filters, with the latter providing improved precision in the gravimetric analysis. The 37-mm glass fiber filters were used on Stage 3 throughout the study. All filters were obtained from Omega Specialty Instruments Co. (Houston, Texas). Gilair-5 sampling pumps (Sensidyne, Clearwater, Fla.) were used to collect all samples at a nominal flow rate of 3.11 L/min.

All pre- and post-trip flow calibrations, for both the RespiCon and sampling pumps, were conducted using the Accuflow digital soap bubble meter (SKC Inc., Houston, Texas). Initially, field calibrations were conducted using a rotameter (SKC Inc.). Both laboratory and field calibrations were soon modified to the sole use of a DryCal (BIOS International, Butler, N.J.). Atmospheric conditions during sampling were monitored using a digital thermometer/hygrometer (Fisher Scientific, Pittsburgh, Pa.). Variables, including wood type, work rate,

TABLE I. Wood Processing Plants

Location (State)	Plant Type	Wood Types Processed	No. of Collected Samples
Okla.	Integrated sawmill/planer mill/plywood	Softwood, hardwood, plywood	212
Va.	Furniture	Hardwood, softwood, engineered wood	271
Ore.	Wood milling	Softwood	181
N.C.	Furniture	Hardwood, softwood, engineered wood	282
Pa.	Wood milling	Softwood, hardwood, engineered wood	290
Minn.	Cabinet	Hardwood, softwood, engineered wood	244
Ind.	Cabinet	Hardwood, softwood, engineered wood	206
Va.	Furniture	Hardwood, softwood, engineered wood	220
Fla.	Plywood	Softwood, plywood	255
N.C.	Furniture	Hardwood, softwood	269
Total			2430

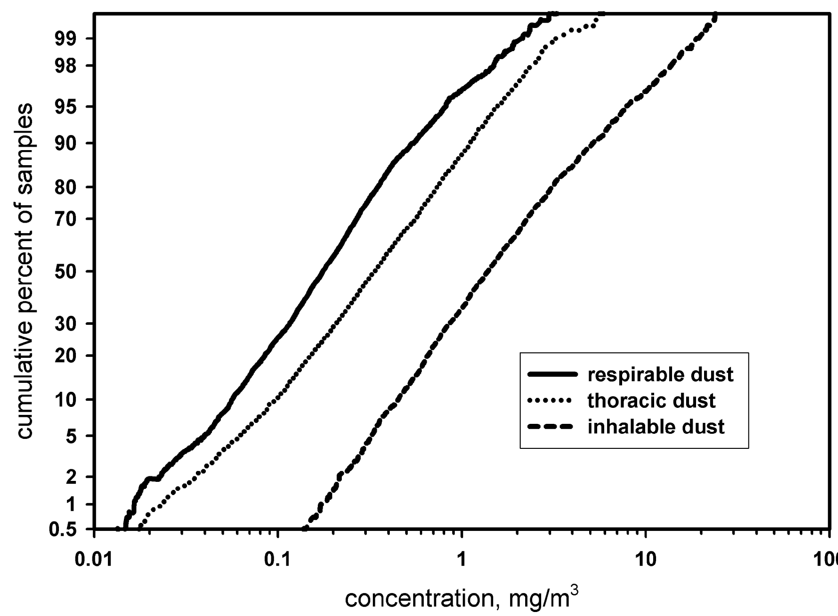

FIGURE 1. Cumulative distributions of size-fractionated dust measurements in the wood processing industry, all plants combined (N = 2430)

activity, task type, manual or automated operation, machine type, job title, potential confounders, and engineering controls, also were recorded at the time of sampling.

Laboratory Analysis and Calculations

All samples were analyzed by gravimetric analysis. Filters were pre- and postweighed 2–3 times each on a Sartorius microbalance ($\pm 1 \mu g$), and the average pre- and post-mass were calculated. Prior to weighing, filters were humidity conditioned in a bench-top chamber for at least 24 hr. Relative humidity in the chamber was maintained at approximately 55% using a saturated sodium dichromate solution. In addition, filters were electrostatically discharged for at least 20 seconds with a Staticmaster alpha emitter (NRD, Grand Island, N.Y.) prior to weighing. After final weights of collected samples had been determined, they were archived in polystyrene Petri slides (Millipore, Billerica, Mass.). Each stage of the RespiCon was subjected to a blank correction using the average weight change of a combination of laboratory, field, and calibration blanks.

According to TSI, the RespiCon sampling efficiency for the extra-thoracic fraction is approximately 33% less in comparison with conventional reference instruments. To correct for undersampling of this size fraction, the manufacturer's guide suggests applying a correction factor of 1.5 to the mass on Stage 3, which collects the extra-thoracic fraction. The appropriateness of this correction factor for wood processing dust was confirmed by Rando et al.[35] in their field comparison of the corrected RespiCon inhalable fraction with that of the IOM sampler. It also was determined, in comparison with reference samplers, that the RespiCon thoracic fraction also required a correction because of apparent oversampling from the extra-thoracic fraction of wood processing dust. The correction equation,[35] which was applied to all sample results for the thoracic fraction in this study, is as follows:

$$Corrected\ thoracic = 0.98\,(sampled\ thoracic) - 0.107\,(inhalable) \qquad \textbf{(1)}$$

Statistical Analysis

The sample results in this study ranged over several orders of magnitude, were skewed toward higher values, and the data distributions qualitatively fit the log-normal reasonably well (Figure 1). Thus, all statistical analyses and tests were performed on the log-transformed data. SPSS statistical software package version 11.5 was used for detailed descriptive statistical analysis of log-transformed data. Exposures were assessed by plant type, job activity/job title, and wood type. Both geometric and arithmetic means were calculated. When there are more than 20 samples, or the geometric standard deviation is too high, Maximum Likelihood Estimate of Mean (MLEM) is a better point estimate than sample mean.[42] MLEM was computed as follows:

$$MLEM = \exp\{y_{avg} + 1/2[(n-1)/n]S_y^2\},\ y = ln\,x \qquad \textbf{(2)}$$

where y is the natural logarithm of individual data points (x), y_{avg} is the arithmetic mean of the log-transformed data (y), n is the sample size, and S_y is the standard deviation of the log-transformed data.

Statistical significance of differences between log-transformed exposure data groups was determined by the analysis of variance technique. Posthoc Tukey's honestly significant difference test was used to determine the significance of the difference, if any, between individual pairs of geometric means.

RESULTS

Of the 10 wood processing plants included in the study, four were furniture manufacturing plants; two were finished cabinet manufacturing and assembly plants; two were wood milling plants producing products such as moldings, dimensional pieces, cabinet components and drawer fronts; one was an integrated sawmill and plywood assembly plant; and one produced only plywood. There were 2430 valid sets of RespiCon samples collected. Of these, 1042, 471, 450, and 467 valid sample sets were collected in the furniture, wood milling, cabinet, and sawmill/plywood plants, respectively. Cumulative distributions of respirable, thoracic, and inhalable dust fractions for all samples collected in the study are shown in Figure 1. Table II shows the corresponding descriptive statistics for the industry as a whole and broken down by plant type, job activity, and wood type.

The mass concentration of dust associated with the inhalable fraction was shown to predominate in this industry. Overall, the geometric mean (GSD) dust concentrations were 1.44 (2.67), 0.35 (2.65), and 0.18 (2.54) mg/m^3, for the inhalable, thoracic, and respirable fractions, respectively. For the inhalable dust fraction, 64.7% of samples exceeded 1 mg/m^3. In contrast, only 22.7% and 3.3% of thoracic and respirable dust samples, respectively, exceeded that level. Averaged across all samples, the respirable fraction accounted for 16.7% of the inhalable dust mass, whereas the corresponding figure for thoracic fraction as a percentage of the inhalable fraction was 28.7%.

Across plant types, there were statistically significant differences ($p < 0.001$) for all three size fractions of dust. Size-fractionated dust levels were highest in the furniture manufacturing and cabinet manufacturing plants, whereas the sawmill and plywood plants generally exhibited the lowest levels of dust. The inhalable dust levels in the sawmill/plywood facilities were significantly lower than all the other plant types.

Among jobs and activities, the process of blowing down with compressed air to clean machinery and work surfaces, and the sanding processes produced the highest size-fractionated dust exposures. Forklift driving, as an activity, was associated with the lowest respirable and inhalable dust fractions, whereas shipping processes exhibited the lowest thoracic dust fraction. The inhalable dust fraction produced from blowing down was significantly higher than that produced by sanding.

Processing of mixed woods (any combination of hardwood, softwood, engineered wood, and plywood) generally was associated with the highest size-fractionated dust exposures, and these were significantly higher in comparison with those associated with processing of hardwood, softwood, and plywood. Of the various wood types, processing of plywood generally produced the lowest dust levels, with the respirable and inhalable fractions being statistically lower than most of the other wood types. For the thoracic fraction, dust from

TABLE II. Descriptive Statistics of Size-Fractionated Dust Measurements for All Plants

	Respirable Dust Fraction (mg/m^3)			Thoracic Dust Fraction (mg/m^3)			Inhalable Dust Fraction (mg/m^3)		
	GM	GSD	MLEM	GM	GSD	MLEM	GM	GSD	MLEM
All samples (N = 2430)	0.18	2.54	0.27	0.35	2.65	0.56	1.44	2.67	2.33
Plant Type									
Furniture (N = 1042)	0.31	2.63	0.50	0.41	2.93	0.72	1.77	2.74	2.94
Cabinet (N = 450)	0.17	2.15	0.23	0.36	2.27	0.50	1.81	2.38	2.64
Wood milling (N = 471)	0.16	2.88	0.28	0.30	2.73	0.50	1.32	2.58	2.06
Sawmill/plywood assembly (N = 467)	0.16	2.27	0.22	0.29	2.18	0.39	0.80	2.20	1.09
Job Activities									
Blow down (N = 33)	0.23	2.23	0.32	0.61	2.46	0.90	2.26	3.39	4.66
Sanding (N = 620)	0.23	2.56	0.36	0.54	2.62	0.86	2.38	2.24	3.76
Debarking (N = 19)	0.23	2.35	0.33	0.53	2.46	0.78	1.11	2.71	1.77
Sawing (N = 407)	0.18	2.55	0.27	0.30	2.68	0.49	1.50	2.60	2.37
Finishing (N = 70)	0.19	2.37	0.27	0.32	2.62	0.51	1.14	2.24	1.57
Milling (N = 429)	0.16	2.55	0.25	0.30	2.50	0.45	1.37	2.32	1.96
Other job activities[A] (N = 852)	0.15	2.41	0.22	0.28	2.46	0.45	1.01	2.50	1.54
Wood Type									
Mixed wood (N = 223)	0.23	2.08	0.30	0.43	2.38	0.63	1.99	2.65	3.20
Hardwood (N = 1446)	0.19	2.53	0.30	0.40	2.66	0.65	1.71	2.60	2.69
Engineered wood (N = 65)	0.15	2.12	0.20	0.24	2.50	0.37	1.64	1.96	2.05
Softwood (N = 660)	0.14	2.47	0.22	0.25	2.52	0.39	0.91	2.03	1.16
Plywood (N = 36)	0.08	2.09	0.10	0.27	2.32	0.38	0.78	2.59	1.22

[A]Other job activities include assembly, boiler operators, clamping, feeding, forklifting, inspection, maintenance, and shipping.

plywood processing was statistically lower than that from processing of mixed and hardwoods.

Tables III through VI present breakdowns of the sampling results grouped by plant type: furniture manufacturing, wood milling, cabinet manufacturing and assembly, and sawmill/plywood, respectively. In the furniture manufacturing plants, size-fractionated dust exposures resulting from blowing down and sanding operations were significantly higher than those from all other job activities. In furniture manufacturing plants, hardwood generated significantly higher thoracic and inhalable dust fractions than softwood; however, the difference between respirable dust fractions was statistically insignificant.

Among the wood milling plants, sanding resulted in the highest size-fractionated dust exposures, which were significantly higher than those resulting from all other job activities. Respirable, thoracic, and inhalable dust fractions generated from softwood were significantly lower than those generated from hardwood, mixed woods, and engineered woods.

Table V shows that in cabinet manufacturing facilities, blowing down and finishing resulted in the highest respirable dust fraction; blowing down and sanding resulted in the highest thoracic and inhalable dust fractions. Respirable, thoracic, and inhalable dust fractions produced by sawing were significantly lower than those produced by all other jobs and activities. Dust levels produced in processing mixed woods generally were higher than those produced from all other wood types. Respirable and thoracic dust fractions that were generated from mixed woods were significantly higher than those generated from hardwood and engineered wood; however, the inhalable dust fraction that was generated from mixed woods was significantly different from that generated from hardwood only.

Table VI shows that in the sawmill and plywood manufacturing plants, the respirable, thoracic, and inhalable dust fractions found in debarking/log yard were significantly higher than those resulting from all other job activities. In addition, size-fractionated dust exposure generated from milling in this industry segment was significantly lower than that generated from all other job activities. The respirable dust fraction generated from plywood was significantly lower than that generated from softwood and hardwood; however, there were no significant differences between thoracic and inhalable dust fractions among the wood types.

DISCUSSION

To the authors' knowledge, this study is the first to provide information on contemporaneous exposures to all three sampling size fractions (respirable, thoracic, and inhalable) of dust in the wood processing industry. The sampling device used in this study (RespiCon) is unique in providing simultaneous measurement of all three size fractions in the same dust sample. The performance of the RespiCon has been evaluated in the wood processing industry and has been shown to meet the ACGIH/ISO/CEN criteria for size-selective sampling

TABLE III. Descriptive Statistics of Size-Fractionated Dust Measurements for Furniture Manufacturing Plants

	Respirable Dust Fraction (mg/m^3)			Thoracic Dust Fraction (mg/m^3)			Inhalable Dust Fraction (mg/m^3)		
	GM	GSD	MLEM	GM	GSD	MLEM	GM	GSD	MLEM
All furniture (N = 1042)	0.31	2.63	0.50	0.41	2.93	0.72	1.77	2.74	2.94
Job Titles and Activities									
Blow down (N = 18)	0.30	1.79	0.35	0.95	2.04	1.20	4.81	2.38	6.86
Milling (N = 191)	0.20	2.58	0.31	0.35	2.61	0.56	1.52	2.39	2.21
PSV (N = 45)	0.17	2.44	0.25	0.29	2.85	0.49	1.13	2.32	1.60
Sanding (N = 374)	0.22	2.81	0.38	0.53	2.86	0.92	2.40	2.71	3.94
Sawing (N = 195)	0.20	2.50	0.30	0.35	2.92	0.61	1.70	2.58	2.66
Other job activities (N = 219)	0.16	2.50	0.25	0.33	3.10	0.62	1.32	2.86	2.28
Assembly (N = 125)	0.17	2.48	0.26	0.39	3.15	0.74	1.63	2.74	2.69
Clamping (N = 23)	0.12	2.91	0.21	0.24	3.29	0.47	1.05	3.59	2.29
Feeding (N = 1)	0.11	—	0.11	0.20	—	0.20	1.10	—	1.10
Forklifting (N = 13)	0.24	1.85	0.29	0.45	1.5	0.48	1.31	1.74	1.51
Inspection (N = 21)	0.18	2.41	0.26	0.38	3.22	0.74	1.53	2.66	2.40
Maintenance (N = 4)	0.13	1.69	0.14	0.14	1.56	0.16	0.62	3.01	0.98
Shipping (N = 32)	0.14	2.78	0.23	0.20	2.6	0.31	0.69	2.67	1.10
Wood Type									
Hardwood (N = 906)	0.20	2.66	0.32	0.42	2.91	0.74	1.81	2.77	3.04
Softwood (N = 83)	0.18	2.66	0.29	0.30	3.34	0.61	1.42	2.27	1.98
Mixed wood (N = 53)	0.20	2.14	0.26	0.35	2.42	0.52	1.70	2.78	2.84

TABLE IV. Descriptive Statistics of Size-Fractionated Dust Measurements for Wood Milling Plants

	Respirable Dust Fraction (mg/m^3)			Thoracic Dust Fraction (mg/m^3)			Inhalable Dust Fraction (mg/m^3)		
	GM	GSD	MLEM	GM	GSD	MLEM	GM	GSD	MLEM
All wood milling plants (N = 471)	0.16	2.88	0.28	0.30	2.73	0.50	1.32	2.58	2.06
Job Titles and Activities									
Milling (N = 139)	0.14	2.74	0.24	0.29	2.47	0.43	1.26	2.35	1.81
PSV (N = 10)	0.14	1.31	0.14	0.22	1.42	0.23	0.83	2.15	1.08
Sanding (N = 88)	0.26	2.46	0.39	0.53	2.64	0.84	2.27	2.43	3.35
Sawing (N = 96)	0.14	3.06	0.26	0.25	2.68	0.41	1.25	2.73	2.06
Other job activities (N = 138)	0.15	3.03	0.27	0.26	2.86	0.45	1.04	2.52	1.59
Assembly (N = 48)	0.17	3.01	0.31	0.29	2.66	0.47	0.93	2.2	1.25
Clamping (N = 32)	0.11	3.2	0.21	0.17	3.25	0.33	0.81	2.95	1.43
Feeding (N = 4)	0.14	2.96	0.22	0.22	2.37	0.29	1.29	2.73	1.88
Forklifting (N = 13)	0.12	2.33	0.16	0.22	3.47	0.45	1.49	3.61	3.19
Inspection (N = 16)	0.18	2.49	0.26	0.33	2.27	0.46	1.14	2.5	1.68
Maintenance (N = 10)	0.14	4.85	0.44	0.24	3.28	0.45	1.32	2.27	1.79
Shipping (N = 15)	0.19	2.93	0.32	0.41	2.14	0.53	1.44	1.56	1.58
Wood Type									
Hardwood (N = 201)	0.22	2.61	0.36	0.42	2.26	0.58	1.53	2.21	2.09
Softwood (N = 181)	0.10	2.67	0.13	0.17	2.63	0.27	0.96	2.78	1.61
Mixed wood (N = 65)	0.25	2.69	0.42	0.51	2.58	0.79	1.97	2.56	3.04
Engineered wood (N = 24)	0.17	2.38	0.21	0.36	2.07	0.46	1.44	2.13	1.89

TABLE V. Descriptive Statistics of Size-Fractionated Dust Measurements for Cabinet Manufacturing and Assembly Plants

	Respirable Dust Fraction (mg/m^3)			Thoracic Dust Fraction (mg/m^3)			Inhalable Dust Fraction (mg/m^3)		
	GM	GSD	MLEM	GM	GSD	MLEM	GM	GSD	MLEM
All cabinet plants (N = 450)	0.17	2.15	0.23	0.36	2.27	0.50	1.81	2.38	2.64
Job Titles and Activities									
Blow down (N = 3)	0.37	2.5	0.49	0.99	1.49	1.04	2.64	1.42	2.75
Milling (N = 83)	0.14	1.56	0.16	0.23	2.15	0.31	1.56	1.83	1.87
PSV (N = 15)	0.34	2.58	0.52	0.57	2.08	0.74	1.40	2.03	1.77
Sanding (N = 146)	0.24	2.15	0.33	0.62	1.91	0.76	2.80	2.26	3.90
Sawing (N = 63)	0.16	2.2	0.22	0.27	2.23	0.37	2.21	2.01	2.81
Other job activities (N = 127)	0.13	2.18	0.18	0.27	1.97	0.34	1.17	2.48	1.77
Assembly (N = 85)	0.13	3.61	0.28	0.27	2.00	0.34	1.07	2.52	1.64
Clamping (N = 6)	0.12	2.73	0.18	0.25	1.45	0.27	1.02	1.42	1.07
Feeding (N = 1)	0.05	—	0.05	0.23	—	0.23	1.05	—	1.05
Forklifting (N = 13)	0.15	2.95	0.27	0.23	1.67	0.26	1.46	2.94	2.50
Inspection (N = 9)	0.13	2.27	0.17	0.32	2.23	0.42	1.21	2.06	1.52
Maintenance (N = 9)	0.18	2.35	0.25	0.26	2.32	0.36	1.15	3.31	2.18
Shipping (N = 17)	0.14	2.73	0.22	0.34	2.01	0.42	1.63	2.16	2.16
Wood Type									
Hardwood (N = 298)	0.16	2.09	0.21	0.37	2.09	0.48	1.71	2.3	2.41
Softwood (N = 6)	0.16	1.28	0.16	0.29	1.28	0.30	1.72	1.94	2.06
Mixed wood (N = 105)	0.24	2.25	0.33	0.43	2.13	0.57	2.18	2.83	3.72
Engineered wood (N = 41)	0.14	1.97	0.18	0.19	2.58	0.30	1.78	1.85	2.14

TABLE VI. Descriptive Statistics of Size-Fractionated Dust Measurements for Sawmill and Plywood Assembly Plants

	Respirable Dust Fraction (mg/m^3)			Thoracic Dust Fraction (mg/m^3)			Inhalable Dust Fraction (mg/m^3)		
	GM	GSD	MLEM	GM	GSD	MLEM	GM	GSD	MLEM
Sawmill and plywood plants (N = 467)	0.16	2.27	0.22	0.29	2.18	0.39	0.80	2.20	1.09
Jobs Titles and Activities									
Blow down (N = 12)	0.14	2.58	0.22	0.28	1.99	0.34	0.63	2.02	0.79
Debarking—log yard (N = 19)	0.23	2.35	0.33	0.53	2.46	0.78	1.11	2.71	1.76
Milling (N = 16)	0.10	2.26	0.14	0.18	2.03	0.23	0.49	1.89	0.59
Sanding (N = 12)	0.14	3.26	0.26	0.24	2.52	0.36	0.70	2.46	1.01
Sawing (N = 53)	0.20	2.29	0.27	0.31	2.15	0.41	0.82	2.32	1.15
Other job activities (N = 374)	0.15	2.19	0.20	0.28	2.12	0.37	0.81	2.16	1.10
Assembly (N = 116)	0.16	2.33	0.23	0.24	2.10	0.32	0.79	2.29	1.08
Boiler operators (N = 6)	0.18	2.26	0.24	0.37	2.13	0.47	0.78	1.76	0.90
Clamping (N = 40)	0.18	1.75	0.21	0.44	1.73	0.51	1.16	1.73	1.34
Feeding (N = 20)	0.21	2.09	0.27	0.26	3.16	0.50	1.12	1.80	1.32
Forklifting (N = 60)	0.12	2.26	0.16	0.29	2.21	0.39	0.70	2.35	0.99
Inspection (N = 30)	0.14	2.02	0.17	0.31	1.83	0.37	0.74	1.93	0.91
Maintenance (N = 22)	0.15	2.82	0.25	0.48	2.38	0.69	1.18	2.34	1.67
Shipping (N = 61)	0.15	1.95	0.18	0.21	1.74	0.24	0.64	1.98	0.81
Wood Type									
Hardwood (N = 41)	0.17	2.02	0.22	0.24	1.98	0.30	0.82	2.17	1.10
Softwood (N = 390)	0.16	1.93	0.20	0.29	2.32	0.42	0.80	2.18	1.08
Plywood (N = 36)	0.08	2.34	0.11	0.27	2.32	0.38	0.79	2.59	1.22

after appropriate adjustment of the extra-thoracic and tracheo-bronchial collection results.[33–37] This is important in light of the fact that certain total and inhalable dust samplers may be susceptible to collection bias resulting from large, inertial particles greater than 100 μm AED that often are produced at high velocity in the wood processing industry from sawing, milling, and other high-energy mechanical processes.[43]

The 10 plants included in this survey were among a candidate pool of more than 400 wood processing facilities that responded to an initial questionnaire and were chosen based on inclusion criteria for the associated epidemiologic investigation.[38] The inclusion criteria focused on size of the work force (at least 150 to 200 workers), completeness of work history records for employees, lack of confounding exposures to respiratory agents other than wood dust, and insignificant use of respiratory protective equipment other than filtering facepieces. Plant selection also was designed to result in a representative distribution of plant types from across the entire industry. Thus, this exposure survey included plants that performed primary, secondary, and tertiary processing of wood materials, that utilized all major processing techniques such as sawing, milling, sanding, etc., and that processed both hardwoods and softwoods, as well as engineered woods and plywood. Therefore, the study results provide an overview of the current state of exposure in the U.S. wood processing industry, although the survey was limited to only relatively large industrial facilities.

Overall, the measured exposures to respirable dust in this study were well within suggested guidelines for industrial workers. Less than 1% of samples were at or above the OSHA permissible exposure limit or ACGIH TLV for respirable nuisance dust (5 mg/m^3 and 3 mg/m^3, respectively), and the overall geometric mean and MLEM (0.18 and 0.27 mg/m^3, respectively) were less than one-tenth of these values. Although thoracic dust exposures were generally about twice as high as the corresponding respirable dust levels, there are no suitable workplace exposure guidelines for nuisance dusts in this sampling-size fraction. In contrast, overall exposures to inhalable dust were generally about six times greater than the corresponding respirable dust exposure. More than half of all samples in this study were above the ACGIH TLV of 1 mg/m^3 for inhalable wood dust, but there were noteworthy differences in the levels of this size fraction, as well as the respirable and thoracic dust fractions, within the study population. Further examination of the study results, by plant type, process, or task, etc., in comparison with previously reported data from the United States and from abroad, is useful in understanding these findings and putting them into proper context.

In this survey, the inhalable dust fraction in the furniture industry had a geometric mean of 1.77 mg/m^3 and a MLEM of 2.94 mg/m^3. These values fall within the middle of the range of those reported by others. Pisaniello et al.[28] reported that the overall geometric mean of personal inhalable dust in the Australian furniture industry was 2.9 mg/m^3; however, in the Netherlands furniture industry, the geometric mean of inhalable dust was reported at 4.14 mg/m^3.[29] Lower concentrations of inhalable dust were reported in two other studies with geometric means of 1.00 mg/m^3 and 0.95 mg/m^3.[44,45] The overall ratio of respirable dust fraction to inhalable dust in the present study was 0.15, which is comparable to the ratio of 0.14 that was reported in the Australian furniture industry.[28]

The present study has shown that inhalable dust had an overall geometric mean of 1.81 mg/m^3 in the cabinetmaking industry. This is considerably lower than that reported for Australian cabinet makers, where the geometric mean inhalable dust was 3.9 mg/m^3.[28] In the present study, the overall arithmetic mean of respirable dust fraction in the cabinetmaking industry was 0.23 mg/m^3; similarly, the study by Sass-Kortsak et al.[46] reported a mean of 0.29 mg/m^3.

In the wood milling and sawmill/plywood assembly plants, the observed overall geometric means of inhalable dust were 1.32 mg/m^3 and 0.80 mg/m^3, respectively. Mandryk et al.[13] reported that inhalable dust in sawmills had a geometric mean of 1.59 mg/m^3. In the Canadian lumber mill, the geometric mean of inhalable dust was 0.98 mg/m^3.[47] In the present study, the geometric means of respirable dust fraction were 0.16 mg/m^3 and 0.27 mg/m^3 in wood milling plants, sawmill/plywood assembly, respectively. The study in New South Wales, Australia, reported that the geometric mean respirable dust fraction was 0.29 mg/m^3 in sawmills.[13]

In the present study, sanding and blowing down processes generally produced the highest concentration of size-fractionated wood dust among the various job activities, except in the sawmills and plywood plants. The geometric means of inhalable dust generated from sanding were 2.40 mg/m^3, 2.27 mg/m^3, 2.80 mg/m^3 and 0.70 mg/m^3 in furniture, wood milling, cabinet manufacturing, and the sawmill and plywood assembly plants, respectively. In the sawmill/plywood assembly plants, sanding was performed almost exclusively by automated machinery, which typically was enclosed or ventilated. Thus, dust production was controlled or limited, and this is reflected in the results for sanding in this industry segment. In contrast, sanding in the other industry segments often involved manual use of powered handsanders (jitterbugs) or stationary belt or wheel sanders. Consequently, personal exposure levels to dust from the sanding process tended to be much higher.

For comparison with the results of the present study for the sanding process, in the Netherlands furniture industry, the geometric means of inhalable dust were 3.95 mg/m^3 for horizontal belt sanders, 8.24 mg/m^3 for hand-held sanders, and 7.07 mg/m^3 for sanding tables; however, in the joinery industry, the inhalable dust concentration generated from sanding was 4.6 mg/m^3.[29] Similar high concentrations were reported in the Australian furniture industry.[28] In the present study, the respirable dust fraction that was generated from sanding had arithmetic and geometric means of 0.39 mg/m^3 and 0.22 mg/m^3 in furniture, 0.30 mg/m^3 and 0.24 mg/m^3 in cabinet manufacturing, 0.45 mg/m^3 and 0.26 mg/m^3 in wood milling, and 0.25 mg/m^3 and 0.14 mg/m^3 in the sawmill and plywood assembly plants. Scheeper et al.[29] reported that respirable dust concentration generated from sanding ranged from 2.01 mg/m^3 to 5.60 mg/m^3, with an average of 4.23 mg/m^3, and that might be related to the small sample size (N = 4). In the cabinetmaking industry, Sass-Kortsak et al.[46] reported that respirable dust concentration generated from sanding had an average of 0.6 mg/m^3.

Blowing down is another activity often associated with high, short-term, and average exposure levels. In the present study, the geometric means of inhalable dust generated during blowing down were 4.81 mg/m^3, 2.64 mg/m^3, and 0.63 mg/m^3 in the furniture, cabinet, and sawmill and plywood assembly plants, respectively. Similarly, lower concentrations were reported in other studies of sawmills where the geometric means of inhalable dust were 0.34 mg/m^3 in the Canadian lumber mills[47] and 0.96 mg/m^3 in British Columbia lumber mills.[48] On the other hand, in the Netherlands furniture industry, cleanup and sweeping workers had the highest inhalable dust concentration of 8.79 mg/m^3.[29]

In the present study, inhalable dust generated from sawing was significantly higher in the furniture and cabinet-manufacturing industries than in wood milling and the sawmill and plywood assembly plants. The geometric means of inhalable dust were 1.70 mg/m^3 in the furniture industry, 2.21 mg/m^3 in cabinet manufacturing, 1.25 mg/m^3 in wood milling plants, and 0.82 mg/m^3 in sawmills and plywood plants. Other studies have reported geometric means of 3.7 mg/m^3 in the Australian furniture industry,[28] 5.0 mg/m^3 in the Netherlands furniture industry,[29] and 0.94 mg/m^3 in Swiss sawmills.[21] In the cabinet manufacturing plants, respirable dust generated from sawing had a geometric mean of 0.16 mg/m^3; similarly, the study by Sass-Kortsak et al.[46] reported that respirable dust generated from sawing had a mean of 0.11 mg/m^3.

The geometric mean of inhalable dust generated during debarking was found to be 1.11 mg/m^3, and was significantly higher than that generated from sawing, sanding, milling, and other job activities in the sawmill/plywood assembly industry segment. In Swiss sawmills, the inhalable dust generated during debarking had a geometric mean of 0.68 mg/m^3.[21]

In the present study, the geometric means of inhalable dust generated during milling were 1.52 mg/m^3 in the furniture industry and 0.49 mg/m^3 in the sawmill and plywood assembly plants; in comparison, the reported levels were 2.8 mg/m^3 in the Netherlands furniture study[29] and 0.67 mg/m^3 in Swiss sawmills.[21]

Hard and mixed woods generally were associated with higher dust exposure in contrast to softwood and plywood. Plywood generally was associated with the lowest dust exposures among the wood types. The observed overall geometric means of inhalable dust were 1.71 mg/m^3 for hardwood, 1.99 mg/m^3 for mixed wood, 0.91 mg/m^3 for softwood, 0.78 mg/m^3 for plywood, and 1.64 mg/m^3 for engineered woods. In part, these results are confounded with industry segment, in that the furniture and cabinet plants more often tended to work with hardwood and mixed woods rather than softwoods and plywood. The extensive milling and sanding operations in the furniture and cabinet industry segments, which tend to produce more dust than other work activities regardless of wood type, partially account for the observation of higher dust levels associated with the hard and mixed woods.

CONCLUSION

This survey, conducted as part of a longitudinal respiratory health study, provides an extensive and statistically robust database of simultaneous exposures to respirable, thoracic, and inhalable particulate matter in the wood processing industry. Dust exposures associated with industry segment/plant type, specific job activities, and wood types being processed were examined and significant correlations determined. Among the various correlates of exposure, higher dust levels were associated with the furniture industry, sanding and blowing down activities, and the processing of hardwood and mixed wood, whereas overall lower exposure levels were observed in the sawmill/plywood assembly industry segment.

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