A Field Comparison of Inhalable and Thoracic Size Selective Sampling Techniques

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We measured inhalable, thoracic, and so-called “total” wood dust exposure in British Columbia lumber mill workers. Particle-size selective sampling was conducted using the GSP and Seven hole inhalable samplers, the PEM thoracic sampler and the 37-mm closed-face cassette “total” sampler. All measurements were full-shift personal samples, obtained from randomly selected workers. We obtained intersampler comparison data for the following pairs of instruments: GSP and 37-mm sampler; GSP and seven-hole sampler (SHS); and PEM and 37-mm sampler. The intersampler measurement ratios were estimated as: GSP/37-mm sampler = 4.2; GSP/SHS = 1.7; and PEM/37-mm sampler = 1.6. The GSP/37-mm sampler ratio is consistent with previously reported findings, while PEM/37-mm sampler and GSP/SHS ratios were both larger than expected. We found that in all comparisons, the measurement ratio had significant variability that was greatest at low ambient dust concentrations. Although it was not possible to attribute the source of the variability to specific sampler types, we concluded that the GSP sampler might be susceptible to “projectile” particles not normally aspirated, and may be vulnerable to direct aspiration of dust from accidentally contacted surfaces. The PEM was designed for environmental monitoring, and it is possible that it is unsuited to the higher particulate concentrations found in some occupational settings. Disparities among inhalable sampling techniques such as that between GSP and SHS should be investigated further in light of the proposed adoption of the inhalable method as an industrial standard. © 1999 British Occupational Hygiene Society. Published by Elsevier Science Ltd. All rights reserved.

Keywords: occupational exposure; inhalable; thoracic; particulate; wood

INTRODUCTION

In Canada and the United States sampling methods for occupational exposure to wood dust are usually gravimetric, and have traditionally utilized filters mounted in 37-mm polystyrene cassettes. While called a “total aerosol” method, the particle size fraction collected by this technique varies with device configuration and flow rate. It is not consistently representative of either the total amount of airborne particulate or the fraction that may enter the respiratory system (Werner et al., 1996). In particular, it is not considered a reliable method for measuring particulate with aerodynamic diameters in the range of 10–100 μm, which are of greatest concern in the study of diseases of the upper respiratory tract such as nasal cancer, a disease associated with wood dust exposure (Hinds, 1988).

For over a decade the American Conference of Governmental Industrial Hygienists (ACGIH) has recommended that particle size selective sampling techniques be used to measure airborne particulate (ACGIH, 1985). The ACGIH is currently reviewing particulate exposures with a view to defining appropriate fractions and mass concentrations to be adopted as particle-size selective Threshold Limit Values (TLVs; ACGIH, 1997). Particle size selective TLVs have been proposed for the inhalable, thoracic and respirable fractions. This study is concerned with only the first two of these. Inhalable dust is defined as the fraction of particulate that may enter the mouth or nose during breathing, while thoracic dust is defined as the sub-fraction of inhalable particulate which may penetrate past the larynx. Both are described by curves relating inhalability and deposition in the respiratory tract to aerodynamic di-
ameter (Figs. 1 and 2), and have been presented in detail elsewhere (Vincent, 1994a,b).

Investigations of the size distribution of wood dust particulate from lumber-milling type operations have found mass median aerodynamic diameters (MMADs) in the range of 15–60 μm. Darcy (1982) showed a bimodal distribution for the rough cutting of mixed hard and softwoods, with MMADs of 29.5 and 0.85 μm for the large and small modes respectively. The interquartile range for the large mode was

Fig. 1. Sampling efficiencies of inhalable samplers and 37-mm closed face cassette (adapted from a laboratory-based intersampler comparative tests, Kenny et al., 1997). Line: ACGIH inhalable curve; vertical bars: interquartile range of wood dust particulate size distribution (rough cutting mixed woods, Darcy, 1982).

Fig. 2. Sampling efficiencies of PEM thoracic sampler (from Marple, 1989), and 37-mm closed face cassette (from Kenny et al., 1997). Line: ACGIH thoracic curve; vertical bars: interquartile range of wood dust particulate size distribution (rough cutting mixed woods, Darcy, 1982).
15–60 μm. Bullock and Laird (1994) reported an MMAD of 15 μm in sawing of particle- and waferboard, and from 3.5 to 20 μm for cleanup jobs. Pisaniello et al. (1991) reported MMADs of 17–22 μm for sawing tasks. It is generally concluded that the major portion of wood dust mass is contributed by particles >10 μm (Hinds, 1988; Pisaniello et al., 1991).

We used particle size-selective sampling methods to obtain 949 personal wood dust exposure measurements as part of an effort to assign exposure levels to a cohort of 26 487 lumber mill workers (Teschke et al., 1998). Because of the suspected health effects of wood dust on both the upper and lower respiratory tract, exposure to both inhalable and thoracic particulate was assessed. Assessment of these fractions provides a more accurate understanding of the true deposition of aerosol in the respiratory system, which is likely to reduce exposure misclassification in epidemiologic studies of respiratory disease.

The air monitoring was conducted at four British Columbia lumber mills. We selected the GSP as our inhalable sampler because it ranked highly in a recent review of six commercially available samplers, giving the most accurate and precise conformation to the recommended sampling efficiency standards (Kenny et al., 1997). Figure 1 shows the sampling efficiency curves of the GSP and 37-mm sampler, and the ACGIH inhalable standard curve.

Thoracic aerosol samples were collected using a personal PM₁₀ sampler, the PEM. The PEM was the only commercially available device for personal sampling of the thoracic fraction. Figure 2 shows the sampling efficiency of the PEM and 37-mm samplers. The PEM gives a sharp cut-off at 10 μm, and its sampling efficiency is therefore considered to only approximate the ACGIH thoracic curve (also shown).

In an earlier cross-sectional study of a British Columbia lumber mill (Demers et al., 1999; Teschke et al., 1999), inhalable samples were collected using the seven-hole sampler (SHS). The SHS is recommended by the U.K.’s Health and Safety Executive for sampling “total-inhalable” dust (HSE, 1993), and it had been found by Chung et al. (1987) and Kenny et al. (1997) to well approximate the published inhalable particulate sampling efficiency standards (Fig. 1).

Publishing comparative field studies has been encouraged to supplement laboratory work and help the introduction of size-selective sampling techniques (Kenny et al., 1997; Werner et al., 1996). Developing “intersampler ratios” comparing 37-mm sampler measurements to particle size selective measurements is problematic however, because the intersampler ratio is dependent on the underlying particulate size distribution and the qualitative homogeneity of the particulate. For the inhalable fraction, Werner et al. (1996) have suggested “working” inhalable to 37-mm sampler “conversion factors” based on industry type, and ranging from 1.0 to 2.5, derived from studies conducted comparing the IOM inhalable sampler (Mark and Vincent, 1986) and the 37-mm sampler. Exposures and industries studied to date have included nickel production (Tsai et al., 1995), nickel electroplating (Tsai et al., 1996), aluminum production (Vincent, 1995), lead smelting (Spear et al., 1997), machining fluids in metal working shops (Wilsey et al., 1996), woodworking (Martin and Zalk, 1998; Vinzents et al., 1995), and welding (Vinzents et al., 1995). To our knowledge, no comparative studies in occupational settings using the GSP or SHS inhalable samplers, nor using the personal PEM thoracic sample have yet been published.

The purpose of this paper is to present the results of analyses used to determine intersampler ratios for wood dust exposure using inhalable and thoracic samplers with the 37-mm sampler. These were derived using side-by-side data collected under field conditions in four lumber mills. Intersampler ratios for GSP to 37-mm sampler, PEM to 37-mm sampler and GSP to SHS were calculated. Full details of the exposure findings of this study will be published at a later date.

MATERIALS AND METHODS

Sampling heads

Inhalable exposures were measured using the GSP sampler (Deha-Haan & Wittmer GmbH, Friolzheim, Germany) and the SHS (JS-Holdings, Stevenage, U.K.). The GSP is of cast metal construction, with a conical aluminium inlet. It has a single 8 mm inlet which faces outward from the subject (Figs. 6 and 7). The SHS is smaller and lighter than the GSP, constructed of injection-molded plastic, with seven 4-mm inlets that face outward from the subject (Fig. 6). The thoracic fraction was measured using the personal PEM monitor (MSP Corp., Minneapolis, MN). The PEM is of aluminum construction (Fig. 6). It is a two-stage sampler, the first stage being an annular impactor which removes particulate >10 μm; particulate smaller than 10 μm are collected on filter media (Marple et al., 1987). 37-mm sampler particulate was measured using a closed-faced 37-mm cassette (SKC Inc., Eighty-Four, PA).

Filters

The SHS’s were fitted with 25-mm diameter 0.45 μm pore size Teflon filters (Costar, U.S.A.). GSPs used 37-mm diameter 5-μm pore size PVC or 2-μm pore size Teflon filters (Gelman, U.S.A.). The PEMs used 37-mm diameter 2-μm pore size Teflon, either with or without a polyolefin support ring.
(Gelman, U.S.A.). The 37-mm polystyrene cassettes used 5-µm pore size polyvinylchloride filters.

**Aerosol sampling**

SKC Brand personal sampling pumps (Eight-Four, PA) were calibrated using a dry piston calibrator (BIOS, Pompton Plains, NJ) to design flow rates ±5%: SHS and 37-mm, 2 l min⁻¹; GSP, 3.5 l min⁻¹; PEM, 4 l min⁻¹. Flow rates in calculations were averages of pre- and post-sample flow rates. Pairs of pumps were attached to workers’ belts, and sampling heads affixed on the same shoulder in the worker’s breathing zone (in approx. 10% of sampling tests, sampling heads were positioned on different shoulders). Samplers were worn for the workers’ full 8–12 h shift, including breaks. All measurements were personal samples.

SHS and 37-mm samplers were loaded and unloaded at our laboratory facilities in Vancouver, BC. GSP filters were transported to and from the sampling sites in manufacturer-supplied filter carriers. The uncapped carrier fitted directly into the GSP sampling head. PEM samplers were also reloaded in the field, with filters transported to and from the site in 37-mm cassettes. Approximately every 10th sample (for all types) was a field blank.

Filters were removed from GSP filter carriers before weighing. All filters were triple weighed pre- and post-sampling on a Sartorius microbalance (Goettingen, Germany), in an environmentally controlled room after filters had been desiccated (60 h) and equilibrated (20°C, 50% RH, >48 h). All sample masses were adjusted by the mean weight change of field blanks.

**Comparison between sampling devices**

Every production, yard and maintenance job at each of the 4 mills was targeted to be sampled at least once with a GSP device and once with a PEM device. For the purposes of the comparative tests we randomly selected participants from within the full group, from all possible sampling days, and asked them to wear side-by-side samplers. Our goal was to obtain 37-mm cassette side-by-side samples for approx. 10% of all GSP and PEM samples. We selected either the 37-mm cassette (C₃7-mm) or SHS concentrations (Cₛₗₐₜ) to be the X-axis in our analyses as they represented the “standards” to which we compared newer methods. It was also assumed that the measuring devices should measure a simultaneous zero concentration and therefore all regressions were forced through zero.

Outliers and observations exerting high leverage (identified by residual analysis and the Cooks D statistic) were removed. Residual analyses demonstrated reasonable homoscedasticity in all comparisons, and therefore no transformation or weighting of variables was required. A t-test was used to compare results of same- and different-shoulder results. All analyses were conducted using STATA Version 5 (STATA Corp., College Station, TX).

**RESULTS**

Table 1 gives a summary of the various sampling regimes. In the full exposure assessment study, 419 GSP and 414 PEM measurements were obtained. Side-by-side tests of GSP and PEM with SHS and 37-mm samplers were subsets of these measurements. GSP and PEM subsets have similar geometric mean and geometric standard deviation to the full datasets, suggesting that they are representative sub-samples. The underlying distributions of all of the GSP, PEM, 37-mm samplers and SHS sample groups were approximately log normal, with large variances (GSDs 2.50–3.34).

**GSP vs 37-mm sampler**

Forty-two GSP/37-mm sampler paired observations were initially obtained. Five pairs were excluded because one of the pair (all 37-mm samples) was below the mass LOD. Three outlying observations were excluded from analyses (GSP/37-mm sampler ratios 39.1–200.7). The remaining GSP/37-mm sampler ratios were highly variable
Table 1. Summary of sampling regimes

<table>
<thead>
<tr>
<th>Device</th>
<th>Fraction</th>
<th>n</th>
<th>GM(^a) (mg m(^{-3}))</th>
<th>GSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full exposure assessment study</td>
<td>GSP</td>
<td>Inhalable</td>
<td>419</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>PEM</td>
<td>Thoracic</td>
<td>414</td>
<td>0.22</td>
</tr>
<tr>
<td>Method comparison sub-samples</td>
<td>GSP</td>
<td>Inhalable</td>
<td>37</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>37-mm</td>
<td>Total</td>
<td>37</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>SHS</td>
<td>Inhalable</td>
<td>38</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>PEM</td>
<td>Thoracic</td>
<td>26</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>37-mm</td>
<td>Total</td>
<td>26</td>
<td>0.16</td>
</tr>
</tbody>
</table>

\(^a\) SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation, SHS, seven-hole sampler.

(Table 2), with a range of 0.3–39.5. The variability was greatest at lower 37-mm sampler dust concentrations, that is when the 37-mm sampler concentrations were < 0.25 mg m\(^{-3}\) (Fig. 3).

The regression model of the GSP vs 37-mm sampler relationship predicted exposure concentrations estimated by the GSP sampler to be approximately 4 times that of the 37-mm sampler (Table 3). Because we selected jobs to be sampled from all production, yard and maintenance jobs in the mill, there was potential for heterogeneity of particulate type and underlying size-distribution. To study this, two additional regression models were examined. One modelled primary particulate exposure assumed to be wood (mainly lumber mill and planer mill departments); a second modeled particulate exposure which potentially included a significant proportion of other dust types (For example, road dust, oil mist, paint, welding fume, and grinding dust). Both sub-models gave similar intersampler ratios to the main model although the wood dust model showed a slight elevation with respect to the non-wood dust model (Table 3). All coefficients were significantly greater than one. A more refined analysis stratified by mill-department showed that intersampler ratios tended to be larger in the areas that processed raw wood (log processing = 4.8, and saw mill = 5.0) and smaller in areas where dried wood was processed (planer mill = 3.5), or where contaminant exposures were expected (maintenance = 3.5, saw filing = 3.1). Factors for shipping and yard departments were 2.6 and 5.3, respectively.

**GSP vs SHS**

Thirty-nine GSP/SHS paired observations were initially obtained. One pair was excluded because the SHS sample was below the LOD. Two outlying observations were excluded from analyses (ratios of 0.6 and 7.5). The remaining GSP/SHS ratios had a range of 0.5–10.8. The variability was greatest at lower SHS dust concentrations (Fig. 4). The results of the regression analysis of GSP vs 7-hole sampler (Table 4) indicate that the exposure estimates of the GSP were approximately 1.7 times that of the 7-hole sampler. This factor did not differ in either the wood dust or “other dust” sub samples, and all intersampler ratios were significantly > 1.

**PEM vs 37-mm sampler**

Thirty-five PEM/37-mm sampler paired observations were initially obtained. Nine paired observations were excluded because the 37-mm sample was below the LOD. Two outlying observations were excluded from analyses (ratios of 0.6 and 7.5). The remaining PEM/37-mm ratios had a range of 0.5–10.8. The variability was greatest at lower SHS dust concentrations (Fig. 4). The results of the regression analysis of GSP vs 7-hole sampler (Table 4) indicate that the exposure estimates of the GSP were approximately 1.7 times that of the 7-hole sampler. This factor did not differ in either the wood dust or “other dust” sub samples, and all intersampler ratios were significantly > 1.

Table 2. Descriptive statistics of the intersampler ratios

<table>
<thead>
<tr>
<th>Description</th>
<th>n(^a)</th>
<th>Ratio median</th>
<th>Ratio mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSP/37-mm cassette</td>
<td>34</td>
<td>7.1</td>
<td>8.6</td>
<td>8.2</td>
</tr>
<tr>
<td>GSP/SHS</td>
<td>36</td>
<td>1.7</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>PEM/37-mm cassette</td>
<td>24</td>
<td>1.8</td>
<td>2.4</td>
<td>2.7</td>
</tr>
</tbody>
</table>

\(^a\) After exclusion of statistical outliers, see text.

Table 3. GSP vs 37-mm sampler. Results of regression analysis of the model: \( C_{\text{GSP}} = \beta C_{\text{37-mm}} \)

<table>
<thead>
<tr>
<th>Description</th>
<th>n</th>
<th>( \beta )</th>
<th>95% CI(^a)</th>
<th>SE</th>
<th>( R^2 )</th>
<th>Model P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full model</td>
<td>34</td>
<td>4.16</td>
<td>3.03-5.29</td>
<td>0.55</td>
<td>0.63</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Wood dust and primarily wood dust</td>
<td>25</td>
<td>4.40</td>
<td>2.83-5.97</td>
<td>0.76</td>
<td>0.58</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Potentially other dust types</td>
<td>9</td>
<td>3.59</td>
<td>2.87-4.30</td>
<td>0.31</td>
<td>0.94</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

\(^a\) CI, Confidence Interval; SE, standard error.
pler and PEM samples were below the LOD. Two outlying observations were excluded from analyses (ratios 0.03 and 8.7). The remaining PEM/37-mm sampler ratios had a range of 0.5–14.0. The variability was greatest at lower 37-mm sampler dust concentrations, that is <0.10 mg m\(^{-3}\) (Fig. 5). The results of the regression analysis of PEM vs. 37-mm sampler (Table 5) indicate that the exposure estimates of the PEM are approximately 1.6 times that of the 37-mm sampler. This factor was slightly elevated for the “other” dust sub group, and all factors were significantly greater than one.

DISCUSSION

GSP vs 37-mm sampler

We found that the GSP measured consistently higher dust levels than the 37-mm sampler in side-by-side tests, as predicted by the sampling efficien-

Fig. 3. GSP/37-mm sampler ratio by 37-mm sampler ambient concentration (mg m\(^{-3}\)).

Fig. 4. GSP/SHS ratio by SHS ambient concentration (mg m\(^{-3}\)).
cies of the two devices in the particle size range expected in a lumber mill environment (Fig. 1). This is consistent with the findings of previous inhalable/37-mm cassette comparative studies (Werner et al., 1996; Martin and Zalk, 1998).

The GSP to 37-mm sampler intersampler ratio was estimated to be approximately 4. Vinzents et al. (1995) reported a ratio of medians of inhalable to 37-mm sampler measurement to be slightly less than 2 at two Scandinavian woodworking sites. Martin and Zalk (1998) reported an inhalable/37-mm sampler ratio of 2–4 at higher dust concentration levels (>0.5 mg m\(^{-3}\)) in their carpentry shop study. The differing ratios reported might be due to differences in underlying particle size distributions resulting from differing machining processes and wood characteristics.

GSP/37-mm sampler ratios ranged from 0.23 to 39.5. This broad range may have been due in part to heterogeneity in underlying particle size distributions. Differences in particle size distributions could be attributed to: (i) variability of processes, for example, planing vs sawing; (ii) variation in wood state, for example, green vs kiln-dried wood or wet vs dry; (iii) variation in factors associated with site and season, such as species processed, processing of frozen wood, or rain-dampening of airborne wood dust; or (iv) variation in particulate exposure composition within jobs, particularly maintenance and yard jobs that may be exposed to contaminating particulate such as oil mist, welding fume, grinding dust, or road dust. To investigate the effect of qualitative differences, we analyzed the data grouped by dust type (for example, primarily wood vs those potentially exposed to other dust types) and by department. There was a small and non-significant difference by dust type. Departments processing green wood showed larger intersampler ratios than

<table>
<thead>
<tr>
<th>Description</th>
<th>n</th>
<th>β</th>
<th>95% CI</th>
<th>SE</th>
<th>R(^2)</th>
<th>Model P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full model</td>
<td>36</td>
<td>1.75</td>
<td>1.48–2.02</td>
<td>0.13</td>
<td>0.83</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Wood dust and primarily wood dust</td>
<td>26</td>
<td>1.76</td>
<td>1.42–2.09</td>
<td>0.16</td>
<td>0.82</td>
<td>&lt;0.0001</td>
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<tr>
<td>Potentially other dust types</td>
<td>10</td>
<td>1.70</td>
<td>1.30–2.11</td>
<td>0.18</td>
<td>0.91</td>
<td>&lt;0.0001</td>
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</table>

Table 4. GSP vs SHS: results of regression analysis of the model: \(C_{\text{GSP}} = \beta C_{\text{SHS}}\)

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<table>
<thead>
<tr>
<th>Description</th>
<th>n</th>
<th>β</th>
<th>95% CI</th>
<th>SE</th>
<th>R(^2)</th>
<th>Model P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full model</td>
<td>24</td>
<td>1.58</td>
<td>1.25–1.92</td>
<td>0.16</td>
<td>0.81</td>
<td>&lt;0.0001</td>
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<td>Wood dust and primarily wood dust</td>
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<td>1.50</td>
<td>1.07–1.93</td>
<td>0.203</td>
<td>0.75</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Potentially other dust types</td>
<td>5</td>
<td>1.83</td>
<td>1.43–2.24</td>
<td>0.146</td>
<td>0.98</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

Table 5. PEM vs 37-mm sampler: results of regression analysis of the model: \(C_{\text{PEM}} = \beta C_{37-\text{mm}}\)
departments where dried wood or contaminant exposures were expected. These differences were consistent with the predicted underlying particle size distribution. We would expect a ratio close to 1 with small particle sizes (such as welding fume and fine dried wood dust) where both GSP and 37-mm cassette have high sampling efficiency, with the ratio increasing as the particle size increases (for example, coarser wood dust) and the efficiency of the 37-mm cassette decreases relative to the GSP sampler.

However, particle size distributions are unlikely to account for all of the variability seen in the GSP/37-mm sampler ratios. Others sources of variability may be associated with characteristics of the individual samplers. As with the more widely used IOM inhalable sampler, the GSP may be vulnerable to “projectile” particles which would normally be too large to be aspirated (Baron, 1998). Variability in individual GSP vs 37-mm sampler ratios was greatest at low 37-mm sampler dust concentrations. This is consistent with loading of the GSP filter with projectile particulate, as the ratio would be most sensitive to projectile loading at low ambient particulate concentrations. Because the inlet of the GSP projects so far from the subject’s body (approx. 6 cm, Fig. 7), it may also be susceptible to direct aspiration of settled particulate from accidentally contacted surfaces. This would be a problem especially for subjects working in cramped and dusty conditions, such as maintenance workers in the lumber mills. This is a time when accurate exposure measurement is particularly important, as it may be a significant contributor to the individual’s overall exposure.

Similar findings of increased variability at low ambient particulate concentration have been reported by Martin and Zalk (1998), who found inhalable (IOM sampler) vs 37-mm sampler ratios in the range of 2–71 when 37-mm sampler dust concentrations were below 0.5 mg m$^{-3}$, and 1.8–4.1 above 0.5 mg m$^{-3}$.

Other sources of variability can be imagined. Approximately 90% of our intersampler comparison tests were conducted with the sampling heads physically adjacent on the same shoulder. Vaughan et al. (1990) showed that variability between samples on different shoulders could be large in comparison to inter-device variability, but we did not see a significant difference between same- and different-shoulder
ratios ($P > 0.7$). We did not attempt to randomize shoulder side for sampler pairs. Variation may have been introduced by weighing the GSP filter without the filter cassette, possibly causing loss of analyte if dust was being retained on the walls of the filter cassette. This is a known source of variability in 37-mm cassettes (Mark, 1990). As new instruments, the painted surface of GSPs had a tendency to be abraded by the opening and closing of the locking ring, causing significant quantities of a fine contaminant to be produced. Great care was required in the field to avoid contamination of samples. The aspiration characteristics of sampling devices vary with wind speed, and susceptibility to wind speed varies between samplers (Vincent et al., 1990). While indoor sampling conditions would be expected to have relatively low wind speeds, higher speeds may have been experienced during outdoor sampling (yard, boom, and shipping departments) which may have differentially influenced sampling efficiencies between samplers.

On a cautionary note, we observed unusually frequent pump failures when using the GSP and polyvinyl chloride filter combination. We attributed this problem to the higher flow rate of the GSP (3.5 l min$^{-1}$) and the propensity for the hydrophilic polyvinyl chloride filter to clog with moisture. The problem was apparently resolved by switching to Teflon filters, which are hydrophobic.

**GSP and 7-hole sampler**

Our analyses show that the ratio of GSP/SHS concentrations was approximately 1.7. From the published laboratory data (Fig. 1), we would expect this ratio to be closer to 1 in the particle size range anticipated for the lumber mill environment. Kenny et al. (1997) suggest that discrepancies between laboratory and field may be due to differences between conditions with respect to particulate size distribution, wind speed, and the presence of localized rather than well-mixed aerosol sources. These authors predicted that differences between types of inhalable samplers could be as large as 40%, based on their laboratory data. Vaughan et al. (1990) reported undersampling by the SHS in side-by-side comparisons with the IOM inhalable sampler, with a mean IOM/SHS ratio of 1.3.
During early sampling efforts we found the SHS susceptible to air leakage due to the loosening of the faceplate (these samples were excluded from analyses). We resolved this by sealing the plate/base joint with electrical tape. Despite this, technical errors generally seem to have a small effect on precision. We calculated pooled coefficients of variation from intra-sampler side-by-side tests and found them to be 12 and 15% for GSP (n=29 pairs) and SHS (n=21 pairs), respectively. While the SHS tests were personal samples, the GSP tests were stationary, and additional methodological issues such as sampler positioning may be of importance when considering precision in personal sampling.

A factor of 1.7 between the two inhalable techniques is a concern, and indicates that substantially different results could be obtained even in the same ambient particulate concentration. We do not know if this problem is uniquely associated with wood-dust monitoring. The ACGIH (1998) has proposed new inhalable threshold limit values for wood dust exposure. The lowest proposed limit is 0.5 mg m$^{-3}$ (Western red cedar), which is in the concentration range giving the highest inter-method variability. Such variability is one of the problems of current “total” dust sampling which size-selective sampling was hoped to address.

**PEM vs 37-mm sampler**

The results indicated a PEM/37-mm sampler ratio equal to 1.6, much higher than anticipated from the relative sampling efficiencies of these samplers in the range of particulate size expected in a lumber mill, and given the sharp cut-off characteristic of the PEM sampler (Fig. 2). Whether this is due to relative oversampling by the PEM or undersampling by the 37-mm sampler method is not understood.

The 37-mm sampler is known to be susceptible to significant wall losses due to static charge, up to 40% of 37-mm sampler mass aspirated at 40 µm MMAD (Mark, 1990). It is also possible that the PEM is unsuited to the higher particulate concentrations found in occupational settings. The PEM has to date primarily been utilized in environmental studies, with average concentrations in the order of 0.08–0.15 mg m$^{-3}$ (Clayton et al., 1993; Thomas et al., 1993; Özkaynak et al., 1996). Robins et al. (1997), however, used PEMS in their study of occupational exposure to metalworking fluids, reporting mean concentrations of 0.13–0.56 mg m$^{-3}$. The precision of the PEM in the higher concentrations found in industrial environments has not, to our knowledge, been investigated. When individual PEM/37-mm sampler ratios were plotted against PEM concentrations, we found a slight positive trend. This may suggest particle bounce, and overloading (data not shown). We observed a few samples in which particulate that had built up on the impactor spilled over on to the filter. The retention ability of the impactor, and therefore the sampling efficiency of the samplers, was probably impaired before actual spillage occurred, and so more samples may have been affected.

Again we found large variability in individual PEM/37-mm sampler ratios, greatest at low 37-mm sampler dust concentrations. For the PEM this is unlikely due to the incursion of projectile particles, as particles propelled (as opposed to normally aspirated) into the PEM would be expected to be removed by the impactor. It should be noted that including outliers (excluded in regression analyses) in these analyses did not affect the pattern of ratio variability for any intersampler comparison.

**Limitations of the study**

A detailed method comparison was not one of the original objectives of this exposure study, and we did not obtain adequate sample numbers for stratification across all qualitatively homogenous groups of interest (for example, jobs or departments). Ordinary least squares regression, though appropriate for a cursory analysis, did not provide a good-fitting model even after exclusion of statistical outliers (although the regression coefficient was stabilized, in effect removing extreme ratios). An underlying assumption of linear regression is that the independent variable is measured without error. In the case of the comparison of two sampling methods, it is not always clear which is the reference method, and very different regression slopes may be calculated for the two possible models. Such was the case in our study. Some authors have addressed this problem by using alternate methods, such as the Deming linear regression analysis that minimize both x and y residuals simultaneously, resulting in a single regression line (Janssen et al., 1998).

Interpretation of our results would have been aided by having particle size distribution data for the sampling sites.

**CONCLUSIONS**

In a side-by-side comparison of particle size selective methods in a lumber mill environment, we found the GSP/37-mm sampler dust ratio to be approximately 4. This is consistent with previously reported results from similar studies, and with the underlying particle size distribution of wood dust.

We found large variability in individual GSP/37-mm sampler ratios. Factors potentially contributing to this variability were the heterogeneous nature of the underlying particle size distribution, vulnerability of the GSP to “projectile” particles, variability in the ambient wind speed, and perhaps losses due to electrostatic effects in the walls of the 37-mm sampler. We suspect that the GSP may be also susceptible to direct aspiration of particulate from acci-
dentally contacted surfaces. The highest degree of variability occurred at lower concentrations. In a comparison of two types of inhalable sampler, we found the GSP sampler to oversample relative to the SHS by a factor of 1.7.

Such large degrees of variability both within GSPs at low concentrations, and between the GSP and SHS, which have both been categorized as “inhalable samplers”, is a concern. This variability may cause a high degree of uncertainty when comparing sampling results to regulatory limits, and in attributing health outcomes to exposure. As suggested by Martin and Zalk (1998), further study into sources of variability in inhalable sampling in the industrial environment are needed.

A surprising result was the PEM/37-mm sampler ratio of 1.6, higher than would have been predicted given the small range of particulate aerodynamic diameters the PEM device is designed to collect. The PEM was originally designed for environmental studies and relatively low aerosol concentrations. It is possible that the device is unsuited to the higher concentrations found in some occupational environments, suggesting further investigation in this area are needed.

We recommend that at least with respect to wood dust, the adoption of particle size selective sampling be made cautiously, until there is a better understanding of the performance of these devices in the industrial environment. Intersampler ratios or “conversion factors” must be used with extreme care. As suggested by Werner et al. (1996), these ratios should probably be used only to reinterpret individual sets of exposure data, and homogeneity of the underlying particle size distribution and the specific device type used should be taken into account.

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