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Excessive Exposure to Silica in the US Construction Industry

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Exposures to respirable dust and silica were investigated among 36 construction sites in the USA. Personal measurements (*n* = 151) were analyzed from 80 workers in four trades, namely bricklayers, painters (while abrasive blasting), operating engineers and laborers. Painters had the highest exposures (median values for respirable dust and silica: 13.5 and 1.28 mg/m^3, respectively), followed by laborers (2.46 and 0.350 mg/m^3), bricklayers (2.13 and 3.20 mg/m^3) and operating engineers (0.720 and 0.075 mg/m^3). Mixed models were fitted to the log-transformed air levels to estimate the means and within- and between-worker variance components of the distributions in each trade. We refer to the likelihood that a typical worker from a given trade would be exposed, on average, above the occupational exposure limit (OEL) as the probability of overexposure. Given US OELs of 0.05 mg/m^3 for respirable silica and 3 mg/m^3 for respirable dust, we estimated probabilities of overexposure as between 64.5 and 100% for silica and between 8.2 and 89.2% for dust; in no instance could it be inferred with certainty that this probability was <10%. This indicates that silica exposures are grossly unacceptable in the US construction industry. While engineering and administrative interventions are needed to reduce overall air levels, the heterogeneous exposures among members of each trade suggest that controls should focus, in part, upon the individual sites, activities and equipment involved. The effects of current controls and workplace characteristics upon silica exposures were investigated among operating engineers and laborers. Silica exposures were significantly reduced by wet dust suppression (~3-fold for laborers) and use of ventilated cabs (~6-fold for operating engineers) and were significantly increased indoors (about 4-fold for laborers). It is concluded that urgent action is required to reduce silica exposures in the US construction industry.

Keywords: construction industry; controls; dust; mixed models; overexposure; silica; variance components

INTRODUCTION

Numerous construction activities, such as abrasive blasting, cutting, drilling and grinding of concrete and masonry and road milling and sweeping, generate clouds of fine dust (Riala, 1988; Blute *et al.*, 1999; Lumens and Spee, 2001; Akbar-Khanzadeh and Brillhart, 2002; Bakke *et al.*, 2002; Linch, 2002; Woskie *et al.*, 2002). Since these dusts generally contain crystalline silica, a potent lung toxin and suspected human carcinogen (IARC, 1997), it is reasonable to ask whether construction workers are overexposed relative to current occupational exposure limits (OELs). Several recent studies document air concentrations of respirable silica in the US construction industry at levels above the current OEL of 0.05 mg/m^3 (NIOSH, 1975; ACGIH, 2002) during everyday operations (Blute *et al.*, 1999; Lumens and Spee, 2001; Akbar-Khanzadeh and Brillhart, 2002; Bakke *et al.*, 2002; Linch, 2002; Woskie *et al.*, 2002) as well as during governmental inspections (Linch *et al.*, 1998). However, the extent of overexposure

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cannot be accurately gauged because the variations in air levels within and between workers have not been reported for the construction trades.

Recognizing that silica is slowly cleared from the lung, the long-term mean exposure received by a worker over months or years is ultimately predictive of lung disease. Thus, a worker's risk of disease exceeds that inherent in the OEL when his or her long-term mean exposure exceeds the OEL, a condition we refer to as 'overexposure'. With knowledge of the mean exposure of each trade, as well as the corresponding within- and between-worker variance components, it is possible to test the probability of overexposure for any particular trade against an *a priori* acceptable value (Rappaport *et al.*, 1995, 1999; Lyles *et al.*, 1997; Weaver *et al.*, 2001).

When a trade has an unacceptable probability of overexposure, some form(s) of intervention is required. If the trade mean exposure is at or greater than the OEL, then trade-level interventions, including engineering or administrative controls, are needed. Furthermore, with evidence of considerable heterogeneity of exposure among trade members, the intervention strategy should reflect the particular interplay of sites, activities and equipment involved (Rappaport, 1991). We define the heterogeneity of exposure within a trade in terms of the proportion of predicted random worker effects that are significantly different from 0 (Rappaport *et al.*, 1999; Weaver *et al.*, 2001).

The current study was motivated by the paucity of information about the overall levels of exposure to respirable dust and crystalline silica (hereafter simply 'dust' and 'silica'), as well as the within- and between-worker variance components, for the US construction trades. Data were compiled from surveys conducted at 36 sites in four construction trades. Using mixed models (Rappaport *et al.*, 1999; Weaver *et al.*, 2001), we estimated the within- and between-worker variance components for each trade as well as the associated probabilities of overexposure, relative to OELs of 0.05 mg/m^3 for respirable silica (NIOSH, 1975; ACGIH, 2002) and 3 mg/m^3 for respirable dust (ACGIH, 2002), and the random worker effects. We then employed the trade mean exposures and proportions of significant random worker effects to optimize control strategies. Finally, we employed a mixed model to evaluate the effects of existing controls and environmental characteristics upon silica exposures in the two trades with greatest representation in our sample (operating engineers and laborers).

METHODS

Construction sites, trades and surveys

As shown in Table 1, data were obtained from 36 construction sites in the Eastern and Midwestern USA that had been surveyed between April 1992 and October 2000. Sites were selected in part to represent activities known to generate silica-containing dust. Multiple surveys were conducted at most sites. The median interval between surveys was 6 days (range 1–580 days) and, with three exceptions (sites 6, 26 and 27), all surveys at a given site were performed within a calendar month. A total of 80 construction workers were investigated from the following trades: painters (PA), bricklayers (BL), operating engineers (OE) and laborers (LA). PA were monitored only during days when they performed abrasive blasting with either sand or coal slag; these workers always wore respiratory protection. BL were typically employed in construction or rehabilitation of commercial buildings, using hand drills, grinders, saws and jack hammers; they occasionally wore respiratory protection. OE and LA worked primarily at outdoor sites typically involving rehabilitation of roads or bridges; they rarely wore respiratory protection. OE operated large pieces of heavy equipment, including vertical drills, backhoes, street sweepers, dowel packs, road milling equipment and crushers, while sitting in open or ventilated cabs ~2–3 m above the work surface. LA worked at ground level, using hand-operated equipment, including drills, saws, jack hammers, chipping guns, rakes and brooms.

Data were compiled from three sources: surveys conducted by the Center to Protect Workers Rights (CPWR) at 13 sites between July 1999 and October 2000; surveys conducted by the National Institute for Occupational Safety and Health (NIOSH) at 14 sites between April 1992 and August 1995; and surveys conducted by the Mount Sinai School of Medicine and Hunter College of the City University of New York (MSSM) at nine sites between September 1997 and December 1998. Data from surveys conducted by CPWR and MSSM have not been reported previously. Data from surveys conducted by NIOSH were previously summarized for other purposes (Linch, 2002). For the current study all primary data were compiled from the original NIOSH reports. Since the construction trades were not reported in most of the NIOSH reports, trades were imputed to these workers based upon descriptions of activities.

Air sampling was performed by occupational hygienists during surveys conducted by NIOSH, MSSM and the Harvard School of Public Health (CPWR data). Surveys of some abrasive blasting and masonry operations (CPWR data) were performed by trained trade members, working in tandem with occupational hygienists. Prior to sampling, these workers attended a 4 day training session to learn air monitoring methods, silica hazards and use of task-based survey methodology (Susi *et al.*, 2000).

Table 1. Descriptions of construction sites and workers investigated

Trade	Site	Workers (*n*)	Measurements (*n*)	Start	End	Location	Type of project	Source
Painter	1	2	4	Jul 99	Jul 99	MA	Industrial rehabilitation	CPWR
Painter	2	2	2	Nov 99	Nov 99	OH	Bridge repainting	CPWR
Painter	3	1	1	Nov 99	Nov 99	OH	Bridge repainting	CPWR
Painter	4	1	1	Jun 00	Jun 00	NJ	Masonry surface preparation	CPWR
Painter	5	2	2	Apr 92	Apr 92	N/A	New construction	NIOSH
Painter	6	1	2	Apr 92	Nov 93	OH	Manufacturing pre-cast concrete	NIOSH
Painter	7	2	2	Sep 92	Sep 92	WV	Bridge resurfacing	NIOSH
Bricklayer	8	1	1	Aug 99	Aug 99	MA	Building rehabilitation	CPWR
Bricklayer	9	1	1	Aug 99	Aug 99	MA	Building rehabilitation	CPWR
Bricklayer	10	1	1	Aug 99	Aug 99	MA	Building rehabilitation	CPWR
Bricklayer	11	2	2	May 00	May 00	MA	Building rehabilitation	CPWR
Bricklayer	12	2	2	Aug 92	Aug 92	PA	Building rehabilitation	NIOSH
Bricklayer	13	2	4	Aug 98	Aug 98	KY	Highway repair	NIOSH
Operating engineer	14	2	2	Oct 00	Oct 00	MA	Road milling	CPWR
Operating engineer	15	2	2	Oct 00	Oct 00	MA	Road milling	CPWR
Operating engineer	16	2	2	Oct 00	Oct 00	MA	Road milling	CPWR
Operating engineer	17	2	2	Oct 00	Oct 00	MA	Road milling	CPWR
Operating engineer	18	3	6	Oct 00	Oct 00	MA	Road milling	CPWR
Operating engineer	19	1	1	Jun 92	Jun 92	WV	Highway construction	NIOSH
Operating engineer	20	1	1	Nov 92	Nov 92	WV	Site excavation	NIOSH
Operating engineer	21	1	2	Jun 93	Jun 93	WV	Highway construction	NIOSH
Operating engineer	22	2	4	Jul 93	Jul 93	PA	Highway repair	NIOSH
Operating engineer	23	1	1	Jul 94	Jul 94	WV	Site excavation	NIOSH
Operating engineer	24	1	2	Aug 95	Aug 95	PA	Road milling	NIOSH
Operating engineer	25	4	7	Aug 95	Aug 95	OH	Highway construction	NIOSH
Operating engineer	26	3	3	Oct 97	Feb 98	NY	Highway rehabilitation	MSSM
Operating engineer	27	3	8	Dec 97	Jun 98	NY	Bridge rehabilitation	MSSM
Operating engineer	28	2	2	Aug 98	Aug 98	NY	Highway rehabilitation	MSSM
Operating engineer	29	1	1	Dec 98	Dec 98	NY	New construction	MSSM
Laborer	14	2	2	Oct 00	Oct 00	MA	Road milling	CPWR
Laborer	15	2	2	Oct 00	Oct 00	MA	Road milling	CPWR
Laborer	16	2	2	Oct 00	Oct 00	MA	Road milling	CPWR
Laborer	17	2	2	Oct 00	Oct 00	MA	Road milling	CPWR
Laborer	18	3	6	Oct 00	Oct 00	MA	Road milling	CPWR
Laborer	30	2	2	May 92	May 92	WV	Bridge demolition	NIOSH
Laborer	21	2	4	Jun 93	Jun 93	WV	Highway construction	NIOSH
Laborer	22	2	4	Jul 93	Jul 93	PA	Highway repair	NIOSH
Laborer	23	1	1	Jul 94	Jul 94	WV	Site excavation	NIOSH
Laborer	24	1	2	Aug 95	Aug 95	PA	Road milling	NIOSH
Laborer	25	4	8	Aug 95	Aug 95	OH	Highway construction	NIOSH
Laborer	31	2	3	Sep 97	Sep 97	NY	Building demolition	MSSM
Laborer	26	2	2	Oct 97	Feb 98	NY	Highway rehabilitation	MSSM
Laborer	27	8	28	Dec 97	May 98	NY	Bridge rehabilitation	MSSM
Laborer	32	2	2	Jan 98	Jan 98	NY	Dam rehabilitation	MSSM
Laborer	33	1	1	Mar 98	Mar 98	NY	Highway rehabilitation	MSSM
Laborer	34	2	2	Apr 98	Apr 98	NY	Bridge roadway repair	MSSM
Laborer	35	2	5	Jul 98	Aug 98	NY	Bridge roadway repair	MSSM
Laborer	36	2	2	Aug 98	Aug 98	NY	Highway rehabilitation	MSSM

Start and End refer to the first and last survey dates; Location refers to the US state; N/A, not available.

Exposure measurements

Personal respirable air samples were collected on 37 mm pre-weighed PVC filters (5 µm pore size). CPWR and NIOSH samples were collected at 1.7 l/min using 10 mm nylon Dorr–Oliver cyclones as pre-separators while MSSM samples were collected at 2.2 l/min using Higgins–Dewell conductive cyclones as pre-separators. Personal monitors were clipped to the workers' lapels regardless of whether respiratory protection was worn.

Dust was measured gravimetrically according to NIOSH Method 600 and silica was measured as α-quartz by X-ray diffraction using NIOSH method 7500 (NIOSH, 1994). One NIOSH measurement was estimated as the mean of five area samples obtained from locations surrounding an abrasive blaster in a small building; these samples were collected at 9 l/min with 37 mm PVC filters connected to 18 mm metal cyclones.

A total of 151 measurements of dust and silica were available from 80 workers. The duration of air sampling ranged from 30 to 561 min with a median value of 315 min and an interquartile range of 227–389 min. Although most of the measurements were based upon a single full-shift sample, some were averages of two or three serial measurements.

As summarized in Table 2, between 11 and 80 measurements were obtained from 8–37 workers in each trade; 1–7 measurements were obtained from each worker and at least one worker in each trade had repeated measurements. Considering the 151 pairs of dust and silica measurements, 24 observations (six for dust and 18 for silica) were below the analytical limit of detection (LOD); these measurements were assigned a value of LOD/√2 for statistical analyses (Hornung and Reed, 1990). One additional measurement was excluded from analysis because field notes indicated that the sampler had become disconnected from the pump during the work shift.

Statistical models

All statistical procedures were performed with SAS software v.8.02 (SAS Institute, Cary, NC). Mixed models were used to characterize the distributions of exposure to dust and silica. Briefly, the models assumed that exposures varied by job group (defined here by the trade), between workers in a given group (i.e. trade members with different mean exposures) and within workers from survey to survey. These models have been thoroughly evaluated with measurements of exposure to welding fumes among construction trades and with exposures of other occupational groups to various contaminants (Rappaport *et al.*, 1999; Weaver *et al.*, 2001).

Let X_{hij} represent the dust or silica concentration (mg/m^3) measured during the jth survey for the ith worker in the hth group and let Y_{hij} represent the natural logarithm of X_{hij}, i.e. $Y_{hij} = \ln(X_{hij})$. The mean and variance of X_{hij} for the hth group are designated as $\mu_{x,h}$ and $\sigma^2_{x,h}$, respectively, and those of Y_{hij} as $\mu_{y,h}$ and $\sigma^2_{y,h}$, respectively. The mixed model relates to the logged exposure levels as follows:

$$Y_{hij} = \ln(X_{hij}) = \mu_{y,h} + \beta_{hi} + \varepsilon_{hij} \qquad (1)$$

(for $h = 1, \ldots, H$ groups; $i = 1, \ldots, k_h$ workers in the hth group; $j = 1, \ldots, n_{hi}$ measurements from the ith worker in the hth group). In Model (1), $\mu_{y,h}$ represents the fixed mean of logged exposures in the hth group, β_{hi} is the random effect of the ith worker in the hth group and ε_{hij} is the random error effect of the jth measurement from the ith worker in the hth group. It is assumed that β_{hi} and ε_{hij} are normally distributed, with zero mean and variances of $\sigma^2_{B,h}$ and $\sigma^2_{W,h}$, representing the between- and within-worker variance components of the hth group. We designate the variance of Y_{hij} as $\sigma^2_{y,h} = \sigma^2_{B,h} + \sigma^2_{W,h}$. Thus, Y_{hij} is normally distributed with mean $\mu_{y,h}$ and variance $\sigma^2_{y,h}$ and X_{hij} is log-normally distributed with mean

$$\mu_{x,h} = e^{(\mu_{y,h} + 0.5\sigma^2_{y,h})}$$

and variance

$$\sigma^2_{x,h} = \mu^2_{x,h}\left(e^{\sigma^2_{y,h}} - 1\right)$$

Table 2. Personal measurements summarized by trade (each measurement includes both respirable dust and respirable silica)

Trade	Job title(s)	Measurements (n)	Workers (k)	Workers with repeat measurements	Measurements per worker	No. of measurements < LOD
Painter	Painter and painter blaster	14	12	2	1–3	2[a]
Bricklayer	Bricklayer and bricklayer/PCC[e]	11	8	1	1–3	4[b]
Operating engineer	Operating engineer	46	23	11	1–6	12[c]
Laborer	Laborer and drill runner	80	37	17	1–7	12[d]

[a]One dust and one silica.
[b]Two dust and two silica.
[c]One dust and 11 silica.
[d]Two dust and 10 silica.
[e]Pointer, caulker and cleaner.

Note also that the log-normal distribution of exposures for the hth group can be characterized with the geometric mean and geometric standard deviation, designated as

$$\mu_{g,h} = e^{\mu_{y,h}}$$

and

$$\sigma_{g,h} = e^{\sqrt{\sigma^2_{y,h}}}$$

respectively.

In a separate analysis, the fixed effects upon silica exposure were explored for all pertinent covariates in the two largest groups in our study (OE and LA). The mixed model used for this analysis is:

$$Y_{hij} = \ln(X_{hij}) = \mu_{y,h} + \sum_{m=1}^{M} \alpha_{m,h} c_{mhij} + \beta_{hi} + \varepsilon_{hij} \quad (2)$$

(for $m = 1, 2, \ldots, M$ covariates), where all common terms are the same as for Model (1) and $\alpha_{m,h}$ is the regression coefficient for C_{mhij}, representing the observed value of the mth covariate during the jth survey for the ith worker in the hth group. Separate applications of Model (2) were performed for OE and LA, with covariates consisting of calendar time and dummy variables for the following effects: indoor work, use of water to suppress dust generation, use of a ventilated cab (OE only) and use of mechanical/dilution ventilation (LA only). Variables were retained in final models at a significance level of 0.10. The same assumptions hold as for Model (1), except that Y_{hmij} is now assumed to be normally distributed with mean

$$\mu_{y,h} + \sum_{m=1}^{M} \alpha_{m,h}$$

where M represents the number of covariates in the final model) and variance $\sigma^2_{y,h}$. The mean and variance of the lognormal distribution under Model (2) for group h and covariate m are given by

$$\mu_{x,hm} = e^{\left(\mu_{y,h} + \sum_{m=1}^{M} \alpha_{m,h} + 0.5\sigma^2_{y,h}\right)}$$

and variance

$$\sigma^2_{x,h} = \mu^2_{x,h}\left(e^{\sigma^2_{y,h}} - 1\right)$$

while the geometric mean and geometric standard deviation are given by

$$\mu_{g,hm} = e^{\left(\mu_{y,h} + \sum_{m=1}^{M} \alpha_{m,h}\right)}$$

and

$$\sigma_{g,h} = e^{\sqrt{\sigma^2_{y,h}}}$$

respectively.

Estimation of parameters and model fit

Model (1) is completely specified for the hth group by mean $\mu_{h,y}$ and the variance components $\sigma^2_{B,h}$ and $\sigma^2_{W,h}$. These parameters were estimated under full and reduced versions of Model (1), assuming either distinct $\sigma^2_{B,h}$ and $\sigma^2_{W,h}$ for each group (full model) or distinct $\sigma^2_{B,h}$ and common $\sigma^2_{W,h}$ for all groups (reduced model). Since reduced Model (1) is more parsimonious than full Model (1), likelihood ratio (LR) tests were performed at a significance level of 0.01, to determine whether it was reasonable to pool $\sigma^2_{W,h}$ across groups (Weaver *et al.*, 2001). Model (2) is completely specified for the hth group and M covariates by mean

$$\mu_{y,h} + \sum_{m=1}^{M} \alpha_{m,h}$$

and the variance components $\sigma^2_{B,h}$ and $\sigma^2_{W,h}$. Since Model (2) was applied separately to OE and LA, these parameters were estimated only under the full model.

Restricted maximum likelihood (REML) estimates of the parameters were obtained under Models (1) and (2) using Proc Mixed of SAS. These estimates are designated with a '^', e.g. under Model (1) $\hat{\mu}^2_{y,h}$ and $\hat{\sigma}^2_{y,h}$ represent the estimated mean and variance of Y_{hij} for the hth group,

$$\hat{\sigma}^2_{y,h} = \hat{\sigma}^2_{B,h} + \hat{\sigma}^2_{W,h}$$

and

$$\hat{\mu}_{x,h} = e^{\left(\hat{\mu}_{y,h} + \frac{\hat{\sigma}^2_{y,h}}{2}\right)}$$

Also, the predicted random effect $\hat{\beta}_{hi}$ of the ith worker in the jth group was obtained under Model (1) via Proc Mixed.

Since data had been pooled over a span of years, profile plots were examined and time trends were investigated with Model (2). No evidence of trends was observed.

Testing overexposure

Exposures to dust and silica were tested in terms of the probability that a worker's long-term mean exposure would be greater than the OEL (Rappaport *et al.*, 1995, 1999; Lyles *et al.*, 1997; Weaver *et al.*, 2001). We define overexposure as the condition where a typical worker in the hth group would have a long-term mean exposure ($\mu_{x,hi}$) greater than the

OEL. The probability of overexposure can be related to Model (1) with the following expression:

$$\theta_h P\{\mu_{x,hi} > OEL\} = 1 - \Phi\left\{\frac{\ln\left((OEL) - \mu_{y,h} - \frac{\sigma^2_{W,h}}{2}\right)}{\sigma_{B,h}}\right\} \quad (3)$$

where $\Phi\{x\}$ denotes the probability that a standard normal variate would fall below the value x. The probability of overexposure for each trade was estimated as $\hat{\theta}_h$ by substituting the estimated parameters, obtained under either full or reduced Model (1), into equation (3). Note that θ_h is undefined under equation (3) when $\sigma_{B,h} = 0$.

The magnitude of θ_h for each group was tested using an approach recommended by Weaver *et al.* (2001) based upon earlier work of Lyles *et al.* (1997) and Rappaport *et al.* (Rappaport *et al.*, 1995, 1999). Basically, the following hypotheses were tested for the hth group:

$$H_{0,h}: \theta_h \geq A \text{ versus } H_{A,h}: \theta_h < A \text{ for } h = 1, 2, \ldots, H \quad (4)$$

where A is an *a priori* acceptable level of overexposure, assigned a value of 0.10. Overexposure was evaluated by applying a test statistic, designated $\hat{T}$, which was constructed in one of two ways depending upon whether $\hat{\sigma}^2_{B,h}$ was non-zero or zero. If $\hat{\sigma}^2_{B,h} > 0$, then $\hat{T}$ was evaluated with a Wald-type test; this was the case for seven of the eight trade/contaminant combinations. In the remaining case, involving dust exposure among BL, $\hat{\sigma}^2_{B,h} = 0$ and an alternative test was used to test whether the group mean was less than the OEL (since the between-worker variance component was very small or zero in this case, the probability of overexposure was very close to the probability that $\mu_{x,h} >$ OEL). In either case, the test statistic was compared to a critical value C_α, at $\alpha = 0.05$ level of significance. If $\hat{T} < C_\alpha$, then $H_{0,h}$ was rejected in favor of $H_{A,h}$ and exposure was considered acceptable; otherwise, when $\hat{T} \geq C_\alpha$, exposure was considered unacceptable. Detailed instructions for computations of $\hat{T}$ and C_α are provided by Weaver *et al.* (2001). Because this test is sensitive to departures from normality, the predicted random effects (i.e. the $\hat{\beta}_{hi}$ values) divided by their standard errors were tested for normality both visually, via q–q plots, and with the Shapiro–Wilks W-test at a 0.10 level of significance. All model fits were deemed acceptable by these criteria.

Heterogeneity of exposure

When an acceptable probability of overexposure cannot be inferred for a particular group, we advocate basing the type of intervention, at least in part, upon heterogeneity of exposure in the group (Rappaport, 1991). We address heterogeneity via the proportion of random effects in the hth group (β_{hi}) that are significantly different from zero (Rappaport *et al.*, 1999; Weaver *et al.*, 2001). Groups with sizeable proportions of significant β_{hi} (>10%, say) can reasonably be regarded as heterogeneously exposed.

RESULTS AND DISCUSSION

Scatter plots

The personal measurements of dust and silica are shown in Fig. 1, with data aggregated by workers in each trade (note that the exposure scale is logarithmic). The measurements show tremendous variability of exposure within and between workers in a given trade. The ranges of exposure are consistent with those presented in other recent investigations of the same US construction trades. For example, levels observed among BL in this study (0.160–29.0 mg/m^3 dust and 0.007–14.2 mg/m^3 silica, $n = 11$) are similar to those reported for hand grinding of concrete at two US sites (0.34–81.0 mg/m^3 dust and 0.02–7.10 mg/m^3 silica, $n = 49$) (Akbar-Khanzadeh and Brillhart, 2002). Likewise, ranges for OE in this study (0.01–3.00 mg/m^3 dust and 0.007–0.800 mg/m^3 silica, $n = 46$) and LA (0.01–21.0 mg/m^3 dust and 0.007–5.90 mg/m^3 silica, $n = 80$) are comparable to those reported elsewhere during highway construction (OE, 0.15–2.39 mg/m^3 dust and 0.008–0.059 mg/m^3 silica, $n = 22$; LA, 0.18–21.8 mg/m^3 dust and 0.008–1.64 mg/m^3 silica, $n = 36$) (Blute *et al.*, 1999).

The comparisons of measurements to the OELs shown in Fig. 1 are striking, particularly for silica, where 116 of 151 observations (77%) exceeded the OEL of 0.05 mg/m^3. Such great exceedance of 0.05 mg/m^3 is generally consistent with other recent US studies [i.e. 50% of OE measurements and 63% of LA measurements during highway construction (Blute *et al.*, 1999), 69% of BL measurements during concrete finishing (Akbar-Khanzadeh and Brillhart, 2002) and 30.8% of LA measurements and 6.8% of OE measurements during heavy and highway construction (Woskie *et al.*, 2002)].

Summary statistics

Median values and ranges are shown in Table 3 for dust and silica exposures in each trade. The fold ranges of daily air levels (maximum/minimum) varied from 181 to 718 within each trade for dust and from 101 to 2030 for silica. Large differences in median exposures were also apparent among trades, with PA having the highest exposures (13.5 mg/m^3 dust and 1.28 mg/m^3 silica, $n = 14$), followed by LA (2.46 mg/m^3 dust and 0.350 mg/m^3 silica, $n = 80$), BL (2.13 mg/m^3 dust and 0.320 mg/m^3 silica, $n = 11$) and OE the lowest exposures (0.720 mg/m^3 dust and 0.075 mg/m^3 silica, $n = 46$).

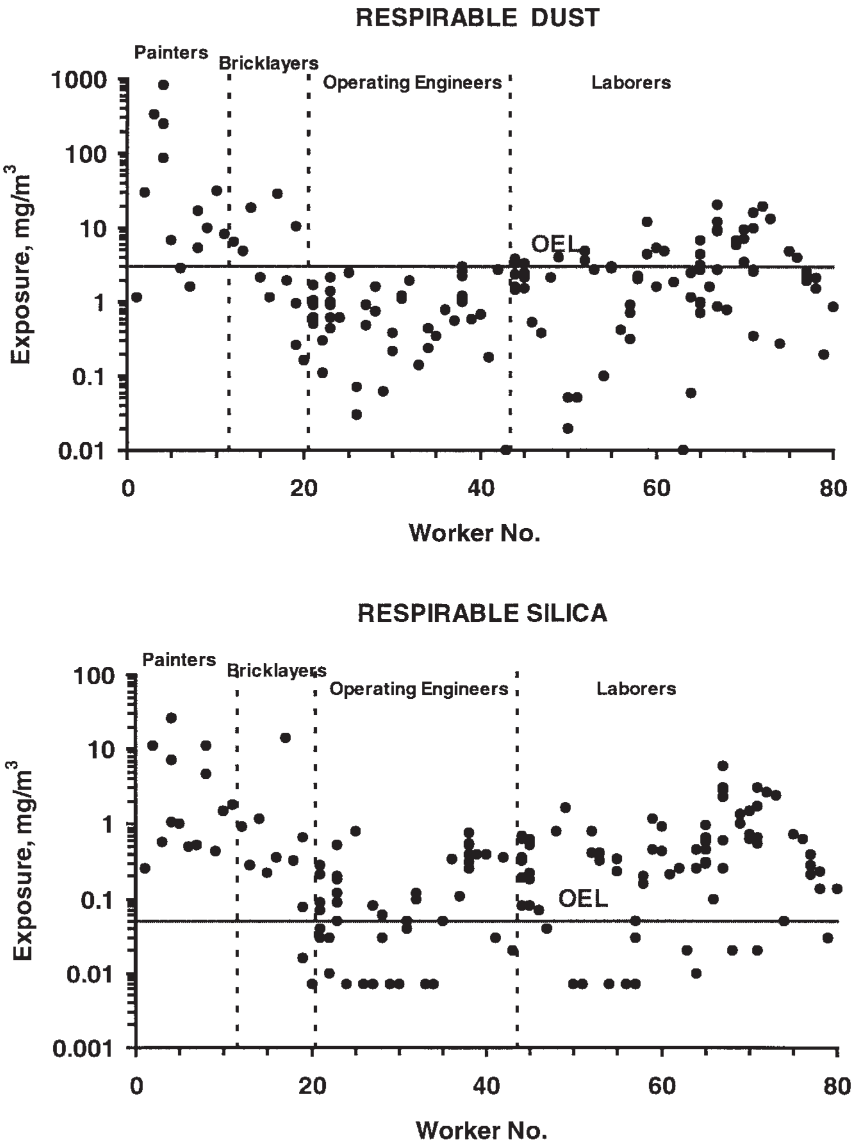

Fig. 1. Exposures to respirable dust and silica among 80 construction workers in four trades. Each point represents a personal measurement. The OELs are 0.05 mg/m^3 for respirable silica (NIOSH, 1975; ACGIH, 2002) and 3 mg/m^3 for respirable dust (ACGIH, 2002).

Table 3. Median levels and ranges of respirable dust and silica exposures for workers in four construction trades

Trade	*n*	Dust (mg/m^3)			Silica (mg/m^3)		
		Median	Range	Max/min	Median	Range	Max/min
Painters	14	13.5	1.16–833	718	1.28	0.260–26.2	101
Bricklayers	11	2.13	0.160–29.0	181	0.320	0.007–14.2	2030
Operating engineers	46	0.720	0.01–3.00	300	0.075	0.007–0.800	114
Laborers	80	2.46	0.01–21.0	210	0.350	0.007–5.90	843

n, number of measurements.

Exposure distributions

The parameters estimated under Model (1) are shown in Table 4. The estimated within-worker variance component ($\hat{\sigma}^2_{W,h}$) was obtained under the full model for dust (P = 0.002 for LR test) and under the reduced model for silica (P = 0.076 for LR test). The estimate of $\hat{\sigma}^2_{W,h}$ ranged from 0.244 to 2.76, depending upon the trade, for dust and was 0.943 for silica in all trades. Since variance components for dust and silica exposures in construction trades have not previously been reported, there are no other estimates with which to compare these results. However, these values of $\hat{\sigma}^2_{W,h}$ are consistent with other published estimates obtained from occupational groups performing intermittent outdoor work (Kromhout *et al.*, 1993; Peretz *et al.*, 1997).

Estimates of $\hat{\sigma}^2_{B,h}$ ranged from 0 to 2.73 for dust and 0.979 to 3.23 for silica, depending upon the trade. These ranges of $\hat{\sigma}^2_{B,h}$ are substantially larger than those typically observed in intermittent outdoor operations (Kromhout *et al.*, 1993; Peretz *et al.*, 1997). Also, $\hat{\sigma}^2_{B,h}$ was greater than $\hat{\sigma}^2_{W,h}$ in seven of the eight combinations of trade and contaminant, the only exception being for dust among BL. This is also unusual based upon data from intermittent outdoor work, where $\hat{\sigma}^2_{W,h}$ tended to be greater than $\hat{\sigma}^2_{B,h}$ (Kromhout *et al.*, 1993; Peretz *et al.*, 1997). Overall, the variance components estimated during construction activities suggest large differences between workers within a particular trade.

Testing overexposure

The results of testing the probability of overexposure are summarized in Table 5. Since it was not possible to demonstrate that $\theta_h < A = 0.10$ in any case, all groups had unacceptable probabilities of overexposure. This outcome was expected because, in most cases, $\hat{\theta}_h >> A = 0.10$ and $\hat{\mu}_{x,h}$ > OEL. Indeed, with θ_h ranging from 64.5 to 100% for silica, it is reasonable to conclude that these trades were grossly overexposed to a well-recognized respiratory hazard. Since the probability of overexposure for a given trade was always greater for silica than for dust, it appears that the OEL of 0.05 mg/m^3 for silica

Table 4. Estimated parameters for distributions of exposure to respirable dust and respirable silica among four construction trades [under Model (1)]

Trade	Contaminant	Model	$\hat{\sigma}^2_{W,h}$	$\hat{\sigma}^2_{B,h}$	$\hat{\sigma}^2_{y,h}$	$\hat{\mu}_{y,h}$	$\hat{\mu}_{g,h}$	$\hat{\mu}_{x,h}$
Painters	Dust	Full	0.981	2.73	3.71	2.65	14.2	90.5
	Silica	Reduced	0.943	0.979	1.92	0.391	1.48	3.86
Bricklayers	Dust	Full	2.76	0.000	2.76	0.954	2.60	10.3
	Silica	Reduced	0.943	3.23	4.17	–1.09	0.336	2.71
Operating engineers	Dust	Full	0.244	1.63	1.87	–0.802	0.448	1.14
	Silica	Reduced	0.943	1.86	2.80	–2.96	0.052	0.210
Laborers	Dust	Full	0.758	2.19	2.95	0.333	1.40	6.09
	Silica	Reduced	0.943	2.29	3.23	–1.68	0.186	0.938

$\hat{\mu}_{y,h}$, $\hat{\sigma}^2_{W,h}$ and $\hat{\sigma}^2_{B,h}$ represent REML estimates of the mean and the within- and between-worker variances, respectively, of the logged exposures for the *h*th trade (exposures given in mg/m^3) obtained under either full Model (1) (dust exposures) or reduced Model (1) (silica exposures); represents the estimated variance of the logged exposures for the *h*th trade; $\hat{\mu}_{g,h}$ and $\hat{\mu}_{x,h}$ represent the estimated geometric and arithmetic means, respectively, of the exposures in the *h*th trade, with units of mg/m^3.

Table 5. Results of testing overexposure for respirable dust and respirable silica among four construction trades [based upon parameters estimated under Model (1)]

Trade	Contaminant	Model	OEL (mg/m^3)	$\hat{\mu}_{x,h}$	$\hat{\theta}_h$	$\hat{T}$	C_α	Decision
Painters	Dust	Full	3	90.5	0.892	4.89[a]	–1.96	Unacceptable
	Silica	Reduced	0.05	3.86	1.000	8.11[a]	–1.96	Unacceptable
Bricklayers	Dust	Full	3	8.26	Undefined[c]	1.35[b]	–6.64	Unacceptable
	Silica	Reduced	0.05	2.71	0.907	4.69[a]	–1.96	Unacceptable
Operating engineers	Dust	Full	3	1.14	0.082	–0.366[a]	–1.96	Unacceptable
	Silica	Reduced	0.05	0.210	0.645	4.64[a]	–1.96	Unacceptable
Laborers	Dust	Full	3	6.09	0.397	3.88[a]	–1.96	Unacceptable
	Silica	Reduced	0.05	0.938	0.881	9.17[a]	–1.96	Unacceptable

OEL, occupational exposure limit (mg/m^3). $\hat{\mu}_{x,h}$ represents the estimated mean of the exposure concentration of the *h*th trade, with units of mg/m^3; $\hat{\theta}_h$ represents the estimated probability of overexposure of the *h*th trade; $\hat{T}$ is the test statistic; C_α is the critical value at an $\alpha = 0.05$ level of significance; Unacceptable, $\hat{T} > C_\alpha$

[a]Wald-type test.

[b]Alternative test.

[c]Undefined indicates that θ_h is undefined under equation (3) when $\sigma^2_{B,h} = 0$.

(NIOSH, 1975; ACGIH, 2002) is more stringent than that of 3 mg/m^3 for respirable dust (ACGIH, 2002) in evaluating exposures of construction workers.

Evaluating the heterogeneity of exposure

Table 6 summarizes the heterogeneity of exposure to dust and silica for the four trades, based upon the percentage of significant (non-zero) random effects β_{hi}. These percentages ranged from <8.3% to 39.1% for all trade/contaminant combinations and were not less than 10%, except, possibly, for PA (dust and silica) and BL (dust only). These results indicate that exposures were highly heterogeneous in the construction industry, particularly for OE and LA.

Taken together, the results summarized in Tables 5 and 6 indicate that exposures were unacceptably high and heterogeneous in the construction industry. Given that the estimated trade mean exposures ($\hat{\mu}_{x,h}$) to silica, which ranged from 0.210 to 3.86 mg/m^3, were all much greater than the OEL of 0.05 mg/m^3, it is clear that trade level interventions (engineering and administrative controls) will be needed to reduce silica exposures in this industry. Furthermore, additional interventions will be needed at the level of the individual worker to control for differences associated with particular sites, activities and equipment in a given construction trade.

Effects of covariates upon exposure to silica

Model (2) was fitted separately to the logged silica measurements obtained from the two largest groups, namely OE (k = 46) and LA (k = 80), using independent variables consisting of calendar time and dummy variables representing indoor work, use of wet dust suppression, use of a ventilated cab (OE only) and use of mechanical/dilution ventilation (LA only). The parameters of the final models are summarized in Table 7 and the corresponding predicted exposures are shown in Fig. 2. Regarding silica exposures of OE, the final model included only the type of cab that was used. When working in ventilated cabs, OE had silica exposures that were ~6-fold lower than those in open cabs (P = 0.053). This finding supports a recent Norwegian study indicating that tunnel workers operating equipment in closed cabs had ~3-fold lower silica exposures than those working in open cabs (Bakke *et al.*, 2002).

Regarding silica exposures of LA, the important variables were the presence of wet dust suppression and indoor work. Wet dust suppression reduced silica exposures about 3-fold (P = 0.015) and indoor work increased exposures about 4-fold (P = 0.001). The 3-fold reduction in silica exposure with wet dust suppression is in line with the results of Thorpe *et al.* (1999), who reported a 3- to 7-fold reduction during wet use of cut-off saws.

Table 6. Uniformity of exposure to respirable dust and silica among four trades of construction workers

Trade	Contaminant	k	No. of significant β_{hi}	Percent significant β_{hi}
Painters	Dust	12	1	8.3
	Silica	12	0	<8.3
Bricklayers	Dust	8	0	<12.5
	Silica	8	2	25.0
Operating engineers	Dust	23	9	39.1
	Silica	23	5	21.7
Laborers	Dust	37	10	27.0
	Silica	37	11	29.7

k, number of workers sampled; β_{hi} represents the random worker effect of the ith worker in the hth trade (this column represent the number of β_{hi} values that are significantly different from 0, P < 0.05).

Table 7. Parameters for distributions of exposure to respirable silica among operating engineers and laborers for various combinations of fixed effects [estimated under full Model (2)]

Trade	Effect	Representing	SE	P value
Operating engineers	$\hat{\mu}_{y,h}$ = –2.721	No control (open cab)	0.3319	
	$\hat{\alpha}_{1,h}$ = –1.905	Ventilated cab	0.9325	0.0527
Laborers	$\hat{\mu}_{y,h}$ = –1.4286	Outdoors without wet dust suppression	0.3348	
	$\hat{\alpha}_{1,h}$ = –1.0695	Wet dust suppression	0.4200	0.0147
	$\hat{\alpha}_{2,h}$ = 1.5124	Indoors	0.4404	0.0014

$\hat{\mu}_{y,h}$ and $\hat{\alpha}_{m,h}$ are REML estimates of the mean of the logged exposure concentration (in mg/m3) of the hth trade and the effect of the mth covariate, respectively.

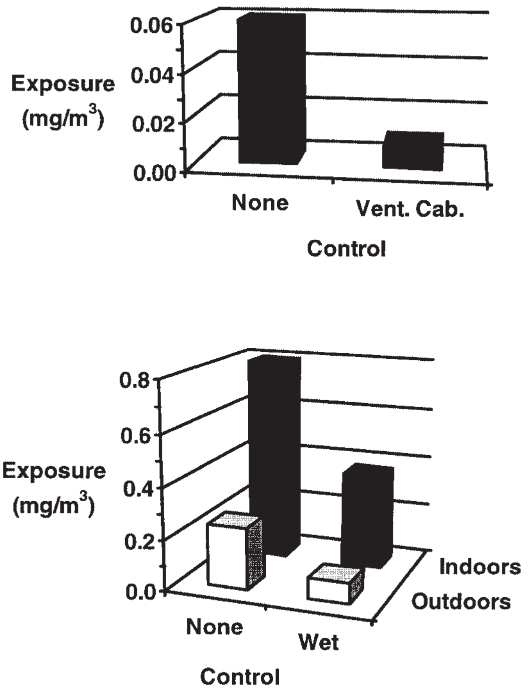

Fig. 2. Respirable silica exposures predicted under full Model (2) for various combinations of controls and workplace characteristics for operating engineers (top) and laborers (bottom) (see Table 7 for estimated fixed effects). Each value represents the predicted geometric mean air concentration for the particular combination of covariates.

In comparing effects of covariates upon exposures for OE and LA, it is interesting that wet dust suppression significantly reduced silica levels for LA but not for OE. Since LA tend to work close to the point of dust generation, it is perhaps reasonable to expect the use of water to reduce dust levels more for LA than for OE, who sit in cabs 2–3 m above ground level. Yet, despite the ~3-fold reduction in silica exposures of LA using wet dust suppression, the predicted geometric mean silica levels are still quite large (0.082 mg/m^3 outdoors and 0.373 mg/m^3 indoors) relative to the OEL of 0.05 mg/m^3. Thus, wet dust suppression would be unlikely to reduce silica exposures of LA sufficiently to provide an acceptable level of overexposure relative to an OEL of 0.05 mg/m^3. On the other hand, OE working in ventilated cabs had a much lower predicted geometric mean than those in open cabs (0.010 versus 0.065 mg/m^3) and approach exposure levels that would be acceptable when $A = 0.10$.

The variance components for exposures to silica, estimated under full Models (1) and (2), are compared in Table 8. For both OE and LA, introduction of significant covariates only moderately reduced $\hat{\sigma}^2_{B,h}$ (15–19% reduction). In a more extensive investigation of three occupational datasets,

Table 8. Estimated variance components for (logged) concentrations of respirable silica among operating engineers and laborers under full Models (1) and (2)

Trade	Model	$\sigma^2_{B,h}$	$\sigma^2_{W,h}$
Operating engineers	1	2.18	0.516
	2	1.85	0.516
Laborers	1	2.25	1.00
	2	1.82	0.775

$\sigma^2_{W,h}$ and $\sigma^2_{B,h}$ represent REML estimates of the within- and between-worker variances, respectively, of the logged

Peretz *et al.* (2002) reported reductions in $\hat{\sigma}^2_{B,h}$ of 35–80%, after numerous fixed covariates were added to mixed models. More work is needed to characterize the sites, activities and equipment used by construction workers so that the sources of exposure heterogeneity within trades can be more fully understood.

CONCLUSIONS AND RECOMMENDATIONS

These analyses of respirable dust and silica exposures in the construction industry provide substantial evidence that construction workers are overexposed relative to the current OELs. In fact, the simple juxtaposition of measurements on the OEL of 0.05 mg/m^3 for respirable silica (Fig. 1) is sufficient to document a pervasive problem with silica exposure in the construction industry. Application of mixed models to the datasets reinforces this notion by showing that typical workers in these trades are very likely to be exposed on average to levels above the OELs (Table 5). Indeed, point estimates of the probability of overexposure for respirable silica approached unity ($\hat{\theta}_h$ = 0.645–1.00) in all trades and the trade mean exposures ($\hat{\mu}_{x,h}$ = 0.210–3.86 mg/m^3) were much greater than the OEL.

Since respirable silica is a potent toxin and suspected carcinogen of the lung, such grossly unacceptable exposures across many US construction sites portend a serious health threat requiring determined action. Indeed, all tools in the occupational hygienists' arsenal should be brought to bear on the problem, including substitution of materials, active methods of dust suppression, ventilation, redesign of equipment and short-term use of respiratory protection. Since construction work involves diverse, predominantly outdoor sites and is largely intermittent in nature, this presents an important challenge for the industry.

Despite the clear need to reduce construction workers' exposures overall, particular control strategies depend, in part, upon the construction trade. The painters in our study all performed abrasive blasting while wearing supplied air respirators and, thus, would have been exposed to much lower silica levels than indicated by the personal sampling. Nonetheless, the enormous silica levels observed during blasting (Fig. 1) raise the question as to whether respiratory protection can be relied upon to sufficiently protect these workers and we recommend that only respirators affording the highest levels of protection (i.e. pressure-demand or positive pressure) be used. It is also important that other workers be isolated from abrasive blasting, because even short periods of silica exposure in the observed range would lead to 8 h averages >0.05 mg/m^3. In addition, the use of sand or silica-containing materials for abrasive blasting should be discontinued and research should be aimed at identifying alternative methods and materials for preparation of surfaces.

Of even greater concern are the large silica exposures observed among BL and LA, who rarely wore respirators in our study. Given that workers in these trades were routinely exposed to silica in the range 0.1–1 mg/m^3 (2–20 times the OEL), substantial reductions in exposure will be required to achieve acceptable levels. In fact, the magnitudes of silica exposure among BL and LA were sufficient to preclude the use of respirators with protection factors of <10. Thus, it is unlikely that disposable and half-mask respirators (the types most often used in the construction industry) would afford sufficient protection to members of these trades while they are operating mechanized hand tools.

The between-worker variance component tended to be much greater than the within-worker variance component for silica exposures. This indicates that construction work is characterized by large differences in average exposures between members of the same trade, a conclusion reinforced by evidence that more than 10% of the random worker effects for silica exposures in three of the four trades were significantly different from 0. Thus, in addition to developing trade level interventions as indicated above, it will also be necessary to investigate many individual sites, activities and types of equipment to arrive at a truly useful intervention strategy for each trade. Our evaluation of a few workplace characteristics indicates that wet dust suppression reduced silica exposures of LA ~3-fold and that ventilated cabs reduced exposures of OE ~6-fold.

In conclusion, we recommend that until such time as the construction industry is prepared to systematically investigate silica exposures at the thousands of sites active across the land, it must foster inexpensive controls, especially use of water to suppress dust. At the same time, methods for isolating workers from dust generation, such as by use of ventilated cabs or workstations, should be actively pursued. Likewise, new methods for locally ventilating sources of dust generation should be sought since our results could not confirm any benefits from mechanical or dilution ventilation. We note with interest a recent paper showing that local exhaust ventilation reduced dust and silica levels by 70–95% under controlled field conditions (Croteau *et al.*, 2002) and we strongly encourage additional work in this area. Finally, respiratory protection programs should be instituted at every construction site, with immediate emphasis given to indoor activities, where silica levels tend to be the greatest.

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