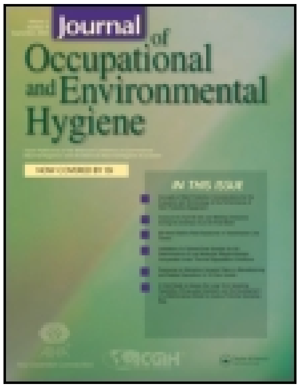

Journal of Occupational and Environmental Hygiene
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uoeh20

Time Variant Exposure Analysis (TVEA): A Measurement Tool for Characterizing Particulate Exposure Determinants in Construction

Andrew J. Kalil [a], Susan R. Woskie [a], Christina Holcroft [a], Michael Ellenbecker [a] & Bryan Buchholz [a]
[a] Department of Work Environment, University of Massachusetts, Lowell

Available online: 17 Aug 2010

Journal of Occupational and Environmental Hygiene, 1: 816–825
ISSN: 1545-9624 print / 1545-9632 online
DOI: 10.1080/15459620490889208

Time Variant Exposure Analysis (TVEA): A Measurement Tool for Characterizing Particulate Exposure Determinants in Construction

Andrew J. Kalil, Susan R. Woskie, Christina Holcroft, Michael Ellenbecker, and Bryan Buchholz

Department of Work Environment, University of Massachusetts Lowell

A work sampling-based approach, time variant exposure analysis (TVEA), was developed for assessment of determinants for particulate air contaminants in dynamic construction environments. To use TVEA, the field researcher records observations at fixed intervals to systematically survey over 30 potential determinants that could affect exposure to three types of particulate matter: quartz-containing dusts, diesel exhaust, and a general grouping of "other particles" that includes welding fume and wood dust. Two field studies were conducted to address questions of inter-rater reliability ($n = 20$) and coding interval appropriateness ($n = 21$) for the TVEA method. At least substantial inter-rater agreement (kappa > 0.60) was obtained for the TVEA variables related to tool or machine use, process, material, source intensity, and source orientation. Kappa values for source direction (0.22–0.38) and number of sources (0.38–0.60) showed comparatively lower agreement for all particulate types. Observation interval appropriateness was analyzed using linear regression to compare a 5-min observation interval "gold standard" with alternate intervals. Regression statistics indicated that while 30 min is an acceptable interval for exposure assessment, 15 min optimizes precision and practicality by ensuring that 95% of all observations differ less than ten percentage points from the "true" values. TVEA is a useful exposure assessment tool for the dynamic construction environment. It is flexible in that only those determinants that are of interest need be coded and the coding interval can be adjusted to accommodate the level of precision desired.

Keywords construction, exposure assessment, particulate matter

Address correspondence to: Susan Woskie, Department of Work Environment, One University Avenue, University of Massachusetts Lowell, Lowell, MA 01824; e-mail: Susan_Woskie@uml.edu.

The content of this article is solely the responsibility of the authors and does not necessarily represent the official views of NIOSH.

The Boston Central Artery/Tunnel Project (CAT) began in 1991 and is scheduled for completion in 2004. The project includes construction of 7.5 miles of highway, much of it underground through the center of Boston, two bridges, and two immersed tube tunnels. During CAT construction, personal samples for exposure to dust, diesel exhaust, quartz, and welding fume were collected across a wide variety of operations in order to characterize worker exposures to particulate matter.(1) During the early phase of this research it became apparent that assessing the factors affecting worker exposure was challenging because of the frequently complex and dynamic nature of work in construction.(2) Different from most other industries, construction work sites are by definition temporary and constantly changing. As an added complication, larger sites may contain several different operations performed by separate subcontracted construction companies only nominally supervised by a primary contractor. The many potential exposure settings in construction make possible a high degree of variability in the number, type, and intensity of particulate sources. A worker's exposure is then a combination of environmental conditions, the phase of construction, the density of equipment and workers on the site, and the specific procedures performed by the worker. At times, a worker's particulate exposure may occur simply through presence as a bystander to a dust-producing process.

One approach to particulate exposure assessment in construction is to use a sampling design based on the tasks performed by workers.(3) With a task-based approach to exposure assessment, separate personal air samples and exposure determinant data are collected for each definable or targeted task, allowing descriptive statistics and models specific to task concentrations to be generated. Task-based sampling has been used in studies of construction work involving lead paint removal on bridges(4) and welding/thermal cutting.(5)

There were three characteristics associated with our study population and exposure assessment goals that would have made task-based sampling difficult to implement. We observed that the workers on sites we had access to were often out of reach, whether in excavations or operating heavy equipment, so that changing samples would have been difficult. Second, the construction work frequently was not composed of easily definable, discrete tasks completed in a sequential order. Third, a goal of our study was to characterize the daily time-weighted average (TWA) for a range of expected exposures. Many construction operations have relatively low mean concentrations of quartz, diesel exhaust, and other particulate exposures. In designing a sampling strategy to assess particulate exposures at relatively low concentrations, it is often not possible to use multiple samplers and still reach the limit of detection.

The Construction Occupational Health Program (COHP) at the University of Massachusetts Lowell has developed an exposure assessment method based on the premise that active observation of the work being performed was necessary to adequately evaluate potential determinants of exposure. This exposure assessment method called time variant exposure analysis (TVEA) is based on work sampling.[6] In traditional work sampling, the proportion of time spent on various activities is estimated by instantaneous observations through the workday. Hansen and Whitehead[7] used work sampling in an exposure assessment for solvents in a printing plant. More recently, Buchholz et al.[8] developed a work sampling method useful as an ergonomic hazard analysis tool in construction work. The TVEA method was designed to use work sampling to systematically survey over 30 potential exposure determinants that could affect exposure to particulate matter.

In addition to describing this exposure assessment method, the other objective of this study was to characterize how well TVEA works as an observational tool for quantifying potential particulate exposure determinants during construction work. To assess inter-rater reliability, pairs of raters observed the same workers under usual field conditions, and each coded the workers following the standard TVEA protocol for coding. Inter-rater agreement was determined using percent agreement and the kappa statistic. The effectiveness of various observation intervals was estimated by comparison with a "gold" standard of 5 min using descriptive statistics and regression analysis.

Description of TVEA

The function of TVEA is to collect data for use in models that explain the exposure levels of quartz, diesel, and other particulate matter experienced by workers. This is contrasted with the use of work sampling to measure the primary variable of interest, as in the case of ergonomic evaluations.[8] The potential exposure determinants evaluated with TVEA were selected and developed based both on our prior observations of particulate exposures during heavy and highway construction work and on industrial hygiene principles of particulate contaminant generation and dispersion.

Particulate sources observed were classified into one of three types: quartz-containing dust, diesel exhaust, or "other particles," a general category that includes wood dust and welding fumes. Quartz-containing dust and diesel exhaust were considered separately because of their widespread presence in heavy and highway construction. For each of the three particulate types, we attempted to collect all information that (1) could be noted by observation, (2) tended to vary from person to person and day to day, and (3) could reasonably be expected to influence exposure. For example, the distance between a worker and the source of particulate generation has been shown to be an important determinant of quartz concentration[9] and may vary in construction depending on the worker's trade and the construction operation performed.

Other variables hypothesized to be key determinants of exposure were the source intensity, worker relationship to source, the process, tool/machine type, plume direction in relation to the worker, source orientation, and the number of secondary sources. The TVEA exposure determinants along with the categories observed during the reliability study are shown in Table I. Depending on the types of work observed, categories for the tool/machine, process, and other determinants would be expected to change. General environmental information that might change over the day was also collected using TVEA. These determinants (categories) included In Enclosure (Yes/No) and Traffic (High, Medium, Low, N/A). Non-time-varying information, such as type of enclosure (e.g., pit or tunnel), was recorded separately.

At each observation interval, spaced 30 min apart for the inter-rater reliability study and the larger COHP exposure assessment, information was collected on up to 32 potential exposure determinants. Filling out the TVEA form takes relatively little time. With practice all of the applicable TVEA variables can be observed within 1 min. A 30-min interval for coding was chosen initially because this interval is shorter than many tasks and was thought to be practical for observing multiple workers on a site. Evenly spaced intervals were considered adequate to avoid bias because processes generating particulate matter in construction usually do not follow a set pattern during the day.

The TVEA data collection sheet (Figure 1) is divided into three sections, one for each targeted particulate type. The Other Particles section includes two special entries used if welders are sampled—Arc On and Helmet Down. The TVEA determinants Source Intensity, Worker Activity, Source Direction, Distance from Source, Number of Sources, and Controls are the same for the three sections; the only difference between them is the particulate source to which they refer (quartz, diesel, or other particles). The diesel section also includes Engine Operating Condition, indicating whether the primary diesel source is at idle or under load at the time of observation.

The number of entries on the data collection sheet at each observation time depends on the sources of particulate exposure present. If the rater did not observe any potential sources of the three types, then only the Source Intensity determinants for Quartz, Diesel, and Other Particles sections are coded (category = No Source Identified). In addition, the Traffic and Enclosure variables are always coded. In using this observational tool, we found it important to develop a protocol to interpret the many different potential exposure scenarios. Additional non-time varying information like enclosure type and machine type for operating engineers were recorded on a separate field data sheet at the start of sampling. Environmental parameters such as temperature, relative humidity, and wind

TABLE I. TVEA Exposure Determinant Categories Present in Reliability Study Datasets

TVEA Exposure Determinant	Particulate Types[A]	Categories
Source intensity	Q, D, P	High, Low, No Source Identified
Worker activity	Q	Operator, Assistor, [B]Associated Process, Bystander
	D	Operator, Associated Process, Bystander
	P	Operator, Associated Process, [B]Bystander
Work process	Q	Chip, Cut , Move, Dig, Mix, Remove Surface, Drill, Blow out
	P	Weld, Cut, Remove Surface, Grind, Sweep, Move, Make Holes
Parent material	Q	Sand,[B] Cement, Poured Concrete, Clay,[B] Soil, Stone[B]
	P	Welding Fume, Wood Dust, Steel Fume, Steel
Source orientation	Q, P	Ground, Ceiling, Wall, N/A
Source direction	Q, D, P	Toward, Away, No Apparent Direction (NAD)
Distance from source	Q, D, P	<3 ft, 3–10 ft, >10 ft
Source machine	Q	Mixer, Excavator, [B]Backhoe
	D	Front-End Loader, Truck,[B] Excavator, Crane, Generator,[B] Compressor, Backhoe, Manlift, Cherry Picker, Crane,[C] Drill Rig[C]
Source tool	Q	Shovel, Hand Tool, Compressed Air,[B] Chipping Gun, High Speed Saw, Hammer,[B] Grinder, Drill[B]
	P	Welding Gun, Drill, Torch, Grinder, High Speed Saw, Drill
Source control	Q	Respirator, Wet, None, General Ventilation[B]
	P	None
	D	None
Additional source(s)	Q	0, 1, 2, 3[C]
	D	0, 1, 2, 3, 4
	P	0, 1, 2
Engine operating condition	D	Idle, Load
In enclosure		Yes, No
Traffic[D]		High,[C] Medium, Low, N/A

[A]Quartz (Q), Diesel (D), Other Particles (P).
[B]Only present in observation interval dataset.
[C]Only present in inter-rater dataset.
[D]Traffic indicates the volume of traffic and the distance between the worker and the roadway adjacent to the construction site.

speed were measured three times per shift and recorded on the field data sheet.

After the sampling has been completed, each TVEA exposure determinant has been coded a number of times (for 8 hours, a maximum of 16 observations at 30-min intervals). Prior to use as an exposure analysis tool, each category of the original TVEA determinant is transformed into a separate percent workday exposure determinant. These transformed determinants estimate the percentage of the sample period a particular condition was true. For example, for each interval there is a source for quartz, the determinant Distance from Source is coded as <3 ft, 3–10 ft, >10 ft. After counting the observations in each of these three categories and dividing by the number of observations, the three resulting determinants are: % Workday <3 ft from Quartz Source, % Workday 3–10 ft from Quartz Source, and % Workday >10 ft from Quartz Source. After these percent of workday variables are merged with non-varying field data and personal air sampling results, they can be used for hazard evaluation or exposure modeling.

METHODS

Data collection for the TVEA reliability studies was conducted from November 1998 to March 1999 as a part of the University of Massachusetts' COHP particulate exposure assessment for heavy and highway construction workers. Four field researchers (raters) in teams of two collected the data for the reliability study. The researchers included three health and safety professionals (master's level training at least) and one industrial hygiene graduate student. Training for use of TVEA included review of the coding manual and several practice runs in the field with an experienced rater. All researchers in the reliability study were experienced in using TVEA concurrent with ongoing COHP personal sampling. Full-shift personal samples for diesel exhaust along with respirable dust and quartz were collected from construction workers participating in the reliability study. Air sampling and analysis methodology is reported elsewhere.(1) Study participants were selected randomly from within construction operations, but the operations themselves were performed mostly by laborers.

Sample#:________________ Date:_________

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Time														
QUARTZ	Visible Emissions														
	Activity														
	Process														
	Surface														
	Material														
	Source Direction														
	Distance														
	Machine														
	Tool														
	Add Sources														
	Controls														
DIESEL	Visible Emissions														
	Actitivity														
	Machine														
	Eng. Oper. Condition														
	Source Direction														
	Distance														
	Add Sources														
	Controls														
OTHER PART.	Visible Emissions														
	Activity														
	Process														
	Surface														
	Material														
	Source Direction														
	Distance														
	Tool														
	Arc on(weld)														
	Helmet down(weld)														
	Add Sources														
	Controls														
	In Enclosure														
	Traffic														

NOTES:____

FIGURE 1. TVEA Data Sheet. Number of columns coded dependent on length of sample period.

Inter-Rater Reliability

For inter-rater reliability, a pair of raters observed the same worker throughout a typical sample period (6 hours) at 30-min intervals. The agreement between raters for each interval entry for each variable on the TVEA data collection form was measured using percent agreement and kappa. The kappa statistic[10] has an advantage over the simple percentage agreement by adjusting for the chance agreement in the proportion of agreement observed.[11] The kappa statistic equals +1 when there is perfect agreement and zero when there is agreement only as far as is expected by chance. Kappa values can be interpreted using the commonly used classification scheme of Landis and Koch.[12] The *a priori* benchmark for inter-rater agreement was a kappa value of at least 0.60 for each TVEA variable, indicating substantial agreement between raters. A value less than substantial (0.60) was presumed to indicate the need for revision of the procedures for coding that particular variable. Confidence intervals for the kappa statistic and the asymptotic variance were calculated using Fleiss's method.[11] Weighted kappa, which assesses partial agreement, was used for the ordinal TVEA exposure determinants (Number of Sources).

Observation Interval

For the observation interval reliability, the TVEA coding occurred at intervals of 5 min instead of the customary 30 min used during the overall exposure assessment. This was considered the shortest feasible interval given the time required for observation and data entry and was therefore used as the gold standard. Percent workday determinants based on time intervals of 10, 15, 20, or 30 min were derived from the 5-min dataset for comparison purposes. For example, the 10-min

TVEA percentage variables are based on information from the first observation from the 5-min dataset and every second observation thereafter; the 30-min observation frequency dataset contains the first observation and every sixth observation thereafter.

The objective of the regression analysis was to quantify relationships between percent workday determinants from the 5-min interval (independent variable) with the alternate intervals (dependent variables) by running separate models. Least squares regression provides more information than any other single statistical procedure about reliability for continuous data used in method comparisons.[13] Because of the relatively small size of the dataset, percentage estimates from the tool/machine determinants were combined for use in the analysis. Comparison statistics from the regression included the parameter estimates, root mean square error (RMSE) and model R^2.

SAS Version 8e statistical package (SAS Institute, Cary, N.C.) was used in the data analysis. PROC IMPORT was used to import the database into SAS. The kappa statistic and its confidence interval and variance were calculated using the Agree option of PROC FREQ. PROC REG was used in modeling the observation interval comparison.

RESULTS

Data was collected from 21 heavy and highway construction workers for inter-rater reliability; 20 had data available for the observation interval analysis. Twelve workers were coded for both analyses. Most of the workers in both populations were laborers.

Inter-Rater Reliability

Two statistics useful in evaluating inter-rater reliability, the percentage of agreement and the kappa statistic, were calculated for each TVEA exposure determinant (Table II). A total of 214 paired 30 min TVEA observations were obtained from 21 construction workers. The number of 30 min interval observations per worker ranged from 8 to 12 with an average of 10.4, and varied depending on the length of the workday of the raters. The three TVEA determinants for Source Intensity along with In Enclosure and Traffic were always coded and had an N of 214 for the 21 workers coded every 30 min. For 148 out of the 214 observations, the Source Intensity variable for quartz was coded as No Source Identified since neither rater observed a quartz-containing particulate source. Therefore, other variables related to quartz exposure were coded only when the Source Intensity variable was coded as High or Low ($n = 66$).

Further, because for quartz either a machine or a tool can function as the particulate source, the sum of the machine ($n = 60$) and tool determinants ($n = 6$) equals the number of observations when a quartz source was present. There were only 79 out of 214 30-min observation intervals when there was a diesel source present (Source Intensity = Hi or Low). For only 24 out of 214 30-min observation intervals was an Other Particle source identified as present (potential source intensity = High or Low).

All of the quartz exposure determinants had substantial or almost perfect agreement except for Source Direction (kappa = 0.38). Of particular note was the substantial or almost perfect agreement for five key exposure determinants: Work Process, Parent Material, Source Orientation, Source Tool, and Source Machine. Similarly, TVEA determinants in the Other Particles section, except for Source Direction and Number of Sources showed at least substantial agreement. Only Source Intensity showed almost perfect agreement for all three contaminant types. Except for Source Intensity, the diesel related TVEA determinants had poorer agreement relative to the other types of particulate matter, including only slight agreement for Source Direction and only fair agreement for Distance from Source. By collapsing the categories for Distance from Source into "<10 ft" and ">10 ft" the value for the kappa statistic increased from 0.33 to 0.51 (fair agreement to moderate agreement).

Observation Interval

Central to the concept of how well TVEA works in estimating exposure determinants is how the presence of exposure sources and their determinants are distributed during the day. Displaying all the observations where a particulate source was noted for each worker using the Source Intensity variable provides some insight as to whether sources tend to cluster around certain parts of the shift or are more or less randomly distributed.

Figure 2 indicates by worker ($n = 20$) whether quartz containing dust, diesel exhaust, or other particles were present at each 5-min interval observation. Diesel exhaust was the most prevalent contaminant in the study population and was present for a median 73% of the observations, quartz-containing particles were present for a median 14% of the observations, and other particles occurred a median 0% of the 5-min intervals (3rd quartile = 11%). Fifteen percent of the workers were in the presence of all three particulate types, 65% had potential exposures to two types, and 20% had exposures to only one type. Figure 2 shows that for each particulate source type (diesel, silica, or other particles) the pattern of exposure is not the same for any of the 20 workers, nor is the pattern of exposure within each worker always the same across the day.

Coding at the 5-min observation interval provided an opportunity to explore changes in the values of the quartz tool/machine determinants when calculated with this and alternate intervals. For the 20 workers in the study, there were 36 tool/machine percent workday estimates for the nine tools or machines observed. In all cases except for one, the difference between the 5-min and the 30-min intervals for each of these determinants was 16 percentage points or less.

The use of the 30-min interval tends either to miss or slightly overestimate relatively rare events (events occurring at one or two 5-min observation intervals during the day). For example, three workers were observed using a grinder during one 5-min observation, and the 30-min interval overestimated % Workday Grinder by an average of 11 percentage points.

TABLE II. Inter-Rater Agreement for TVEA Estimated Exposure Determinants

TVEA Exposure Determinant	N	Percent Agreement (%)	Kappa (95% CI)	Level of Agreement[A]
Quartz				
Source intensity	214	94	0.87 (0.81–0.94)	Almost perfect
Worker activity	66	91	0.83 (0.70–0.96)	Almost perfect
Work process	66	89	0.83 (0.72–0.95)	Almost perfect
Parent material	66	99	0.90 (0.72–1.00)	Almost perfect
Dust source orientation	66	86	0.75 (0.60–0.90)	Substantial
Source direction	66	68	0.38 (0.18–0.58)	Fair
Distance from source	66	88	0.77 (0.62–0.92)	Substantial
Source machine	6	100	1.00 (1.00–1.00)	Perfect
Source tool	60	92	0.86 (0.75–0.98)	Almost perfect
Number of sources[B]	66	77	0.60 (0.44–0.77)	Substantial
Dust control	66	95	0.87 (0.74–1.00)	Almost perfect
Diesel				
Source intensity	214	95	0.89 (0.83–0.95)	Almost perfect
Worker activity	79	89	0.43 (0.18–0.68)	Moderate
Source direction	79	54	0.14 (0.01–0.27)	Slight
Distance from source	79	87	0.33 (0.10–0.57)	Fair
Source machine	79	77	0.73 (0.62–0.84)	Substantial
Engine operating condition	79	75	0.46 (0.26–0.66)	Moderate
Number of sources[B]	79	63	0.41 (0.25–0.57)	Moderate
Other particles				
Source intensity	214	95	0.78 (0.67–0.89)	Substantial
Worker activity	24	96	0.92 (0.75–1.00)	Almost perfect
Work process	24	96	0.91 (0.74–1.00)	Almost perfect
Parent material	24	96	0.91 (0.75–1.00)	Almost perfect
Source orientation	24	100	1.00 (1.00–1.00)	Perfect
Source direction	24	58	0.25 (0.02–0.48)	Fair
Distance from source	24	88	0.78 (0.55–1.00)	Substantial
Source tool	24	96	0.91 (0.75–1.00)	Almost perfect
Number of sources[B]	24	75	0.38 (0.05–0.72)	Fair
Other				
In enclosure	214	89	0.75 (0..65–0.84)	Substantial
Traffic	214	91	0.79 (0.70–0.88)	Substantial

[A] Agreement scale based on Landis and Koch (1977) kappa evaluation criteria.
[B] Weighted kappa.

Likewise, the 30-min interval missed the one or two observations from the 5-min dataset for three workers using hand tools. The same trends shown in the 30-min interval comparison appear with the other alternate intervals but to a progressively lesser extent as intervals decrease. The differences between the percent workday 5-min based estimate and the estimates for 10, 15, 20, and 30 min were computed. Boxplots of the differences between the percent workday estimates for the 5-min observations and percent workday estimates for each comparison interval are shown in Figure 3. These plots show that the mean difference for all alternate intervals is close to zero. At intervals of 10 min and 15 min, the largest differences are less than 15% of the estimate provided by the 5-min interval.

Regression analysis was performed to allow a quantitative comparison of the changes in values of the TVEA percent workday exposure determinants as a function of the interval between observations (Table III). Due to the low number of observations available, the TVEA tool/machine percent workday exposure determinants for all sources (quartz, diesel, and other particles) were combined. The percent workday estimates for alternate observation intervals (y-values) were regressed against the 5-min interval percent workday estimates (x-values). This produced four models, one for each alternate observation interval (10, 15, 20, 30 min). Since the intercept was not statistically significant in any model, it was dropped to make interpretation easier, that is, forced through zero. The changes in R^2, parameter estimates, and RMSE for all of the

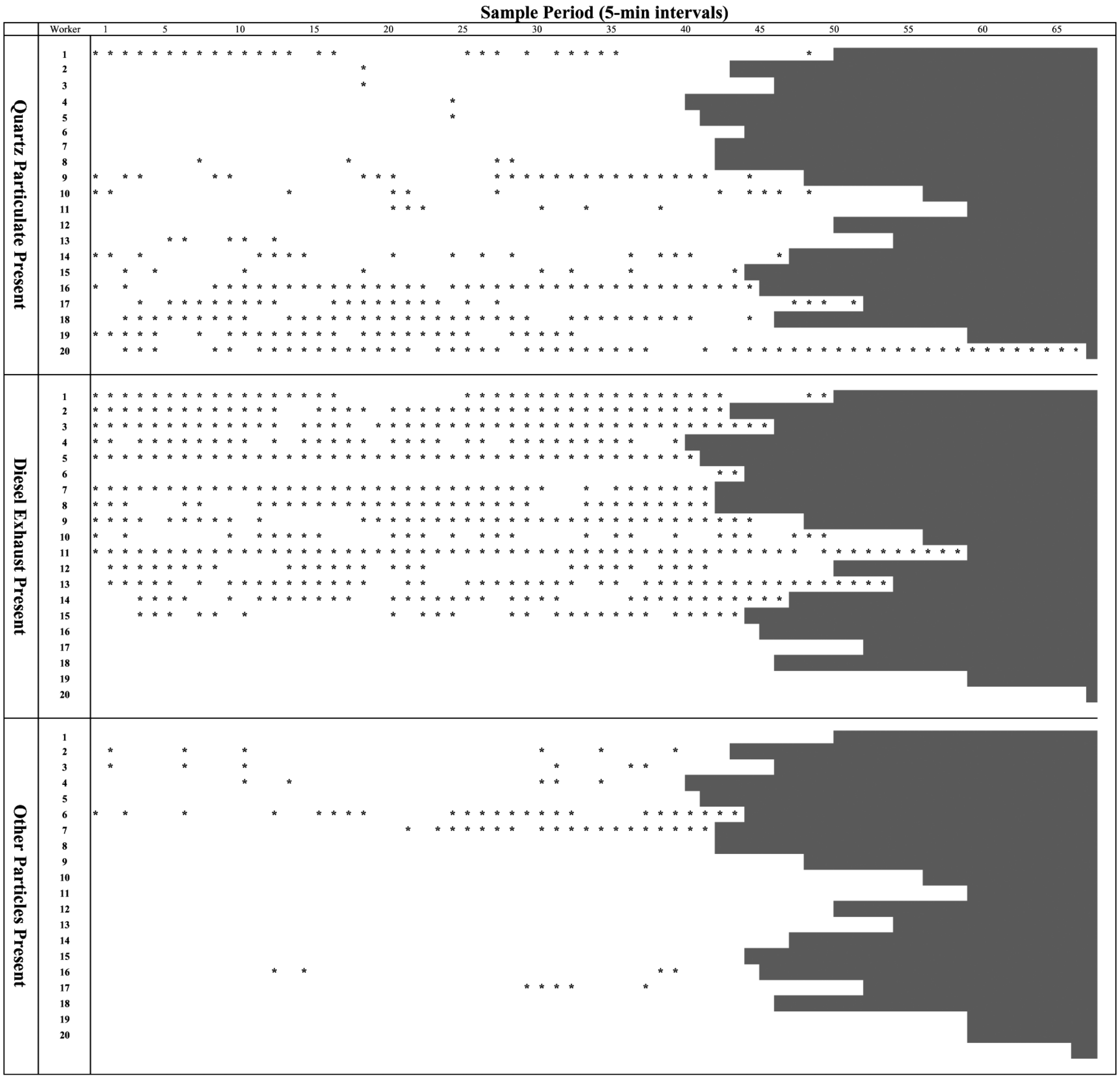

FIGURE 2. Presence of quartz, diesel, and other particles during TVEA 5-min interval observations. Asterisk indicates presence of particle type in that 5-min interval. Start of shaded area indicates the end of sample period for each worker.

dependent variables showed increased accuracy in predicting the 5-min interval as the coding interval decreased.

DISCUSSION

Particulate exposure assessments for heavy and highway construction activities should take into account the dynamic nature of the factors that influence exposure in construction. Workers in the same trade and operation can show a high variability in daily TWA exposure concentrations for quartz and other types of particles;[1] therefore, an approach based solely on these groupings may result in inaccurate exposure estimates. The COHP developed TVEA as a means to estimate time-varying particulate exposure determinants of construction workers. TVEA and other non-time-varying exposure determinants were useful in describing the mixed exposure encountered by workers in heavy and highway construction work. In addition, these exposure determinants were also significant in explaining the variability in daily TWA quartz exposures using multivariate modeling.

Inter-Rater Reliability

Reliability refers to the reproducibility of a measurement. It provides insight as to the extent to which a particular method will provide the same results in repeated measurements or the extent to which different observers agree in assessing the same phenomena. Reliability is a prerequisite for method validity.[14] In the case of individual TVEA variables, reliability depends

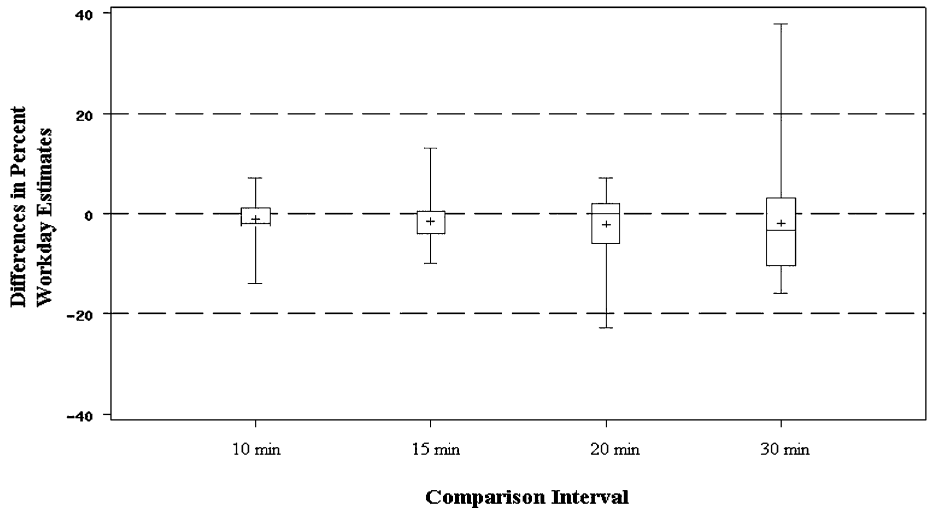

FIGURE 3. Comparison of differences in TVEA tool/machine percent workday exposure determinants based on 5-min observation interval with those based on alternate observation intervals (n = 36). Lower and upper ends of box cover the 25th to 75th percentile. The vertical line in box indicates the median; plus symbol indicates mean. Whiskers show maximum and minimum values.

largely on how well the categories of different exposure conditions are defined in a protocol and on the observational skills of raters in discerning those differing conditions of exposure in the construction setting. In future applications of TVEA, feedback will be solicited from raters as to where difficulties arise in determining which TVEA variable category is correct.

Substantial to perfect inter-rater agreement as measured by the kappa statistic was obtained for 20 of the 29 TVEA exposure determinants tested. The quartz and other particles variables related to tool or machine use, process, material, source intensity, and orientation all had substantial to almost perfect inter-rater agreement. Raters were almost always able to recognize when particulate sources were present and agree on their intensity for these two contaminant classes. A high level of agreement was expected and obtained for the tool/machine use, process, and material variables, since they are relatively easy to categorize for raters with knowledge of common construction processes; they are not subjective measures. Raters were also able to obtain substantial agreement on Distance from Source for quartz and other particles.

TABLE III. Linear Regression of Percent Workday Using Tool/Machine Based on 5-Min Interval Observations with Alternate Interval Observations (n = 53)

Observation Interval (min)	Root Mean Squared Error (RMSE)	Parameter Estimate (Standard Error)	R^2
30	9.75	0.94 (0.03)	0.91
20	6.67	1.04 (0.02)	0.96
15	4.72	0.99 (0.02)	0.98
10	3.95	1.00 (0.01)	0.99

Regression Model

%Workday(Alternate Interval) = B_x(%Workday 5-min Observation Interval)

(Intercept not significantly different from 0 and not included in final model)

The only TVEA exposure determinant that showed less than substantial agreement for all the contaminant types was Source Direction (the movement of particles in relation to source and the worker), which had only fair to slight agreement. The categories for the Source Direction variable are (1) Toward, (2) Away, and (3) No Apparent Direction. Determining the source direction in relation to the worker is difficult when the particulate source may be nearly invisible depending on the source intensity, lighting, observation distance and other factors. The kappa statistic did not improve after collapsing the categories into two: (1) Toward and (2) Away or Not Apparent. Although not always feasible, agreement on source direction might be improved by placing a device capable of determining the wind direction on or near the worker.

The Number of Sources TVEA exposure determinant had only moderate and fair agreement for the diesel exhaust and "other particles" categories respectively. Agreement for this exposure determinant may have been problematic for the raters, since even though the TVEA protocol discusses how to determine whether or not to include a source within a 50-ft perimeter around the worker, it can be difficult to judge whether secondary sources should be considered as part of the work area. In addition, the terrain on a construction site often obscures raters' views depending on their vantage point. To increase reliability for Number of Sources, additional training could be provided for the raters in what constitutes secondary particulate sources; raters could use portable distance measuring devices to locate 50-ft perimeter markers.

Overall, the agreement for the TVEA exposure determinants for diesel exhaust was relatively low. Five of the seven exposure determinants related to diesel exhaust had kappa values less than 0.60. Diesel exhaust may have been more difficult to characterize than the other source types because of the nature of this particulate source: most diesel sources were mobile and heavy equipment was often at a distance or obscured from the raters. The agreement for Distance from Source was only fair. While for operating engineers the distances from the primary diesel source usually remains constant, for example, the heavy equipment operator is sitting in a cab at a fixed distance from the tailpipe, the laborers examined in this study tend to be bystanders at heavy equipment operations and move around in relation to diesel sources. In the case of diesel exhaust, improved reliability would likely occur by collapsing the three Distance from Source categories into $<$20 ft and $>$20 ft. Unlike the other particulate types, few workers are within 3 ft of a diesel source. It is likely most construction workers are either at a lengthy distance from the exhaust of any heavy equipment or within 20 ft. An improved kappa value was obtained with the present data after collapsing "$<$3 ft" and "3–10 ft" into one category.

For the Worker Activity determinant, it may have been difficult to decide whether the worker being sampled was a bystander or if an associated process category (process related to the operation of the sampled worker) was applicable. The agreement for Worker Activity could likely be improved with additional training or by clarifying TVEA categories for this determinant. It may have been difficult for raters to agree on whether diesel engines were at idle or under load when coding Engine Operating Condition, since the agreement was only moderate. The amount of fume emitted from the exhaust of diesel machinery depends greatly on the type, age, maintenance, and use of equipment, limiting the usefulness of the exhaust plume as a cue to operating conditions. In addition, it is not always obvious when cranes are under load. Improvement in the reliability of this exposure determinant will require development of clearer guidelines on how to judge engine operating conditions or use of real-time instrumentation on the equipment to monitor engine load across the day. The real-time engine load recording devices currently available are used in intensive single equipment emission studies and would need to be adapted for everyday field sampling use.

Observation Interval

Of interest for exposure assessment in construction is whether the appearance of particulate sources follows any discernable pattern. For example, particulate exposures could be limited at the start of the day, increase in frequency midday, and decrease in frequency as the end of the day approached. However, visual inspection of source occurrence suggested that there was no discernable pattern across the workday. The randomness of potential exposure occurrence can make the work of the site safety officer more difficult, since even though some workers are in the presence of dusty processes more often, the timing may not be predictable. The data clearly showed that an observation at one point or even a few points during the shift might not be sufficient to truly characterize the exposures for the workday.

For our exposure assessment, the standard time between coding intervals for the TVEA exposure determinants was 30 min. Even though this interval made sense both logistically and from our observations of construction work, there were unanswered questions as to the optimal time interval for coding. Ideally, the coding interval should provide adequate precision in estimating exposure determinants. At the same time, the interval must be reasonable in terms of the workload it places on the rater. The true gold standard for this study would have been continuous observation of all the TVEA variables by a third rater or video camera. However, for practical reasons, we assumed that a 5-min observation interval was the gold standard. The use of multiple video cameras on site was not considered practical in the construction environment and unlikely to capture all the data elements with adequate clarity. The use of a third rater for continuous recording was also considered impractical due to unavailability of sufficient personnel.

The differences between percent workday estimates based on the 5-min versus 30-min intervals were due in large part to the short and infrequent tasks that occurred for some workers in the sample population. In those cases where an infrequent short-term task was missed, variables related to that task would tend to be underestimated; whereas if a short-term infrequent task was observed, the resulting variables would tend to be overestimates of the percent of the workday. For instance, if a worker spends 10 min cutting concrete blocks at a time that does not correspond to the coding interval, it is possible that this exposure may never be recorded. Alternatively, if with the 30-min coding interval an observation takes place by chance when this short-term task was performed, then the magnitude of the exposure determinant will be overestimated because of the relatively small number of observations. Therefore, where short-term tasks with significant exposure potential are likely to occur, a coding interval of less than 30 min should be used or a task-based sampling approach considered.

Results from the regression analysis showed that the percent workday estimates for the TVEA tool/machine exposure determinants improved as the comparison interval decreased from 30 min to 10 min. Since the RMSE estimates the sample standard deviation, a RMSE of 9.75 for the 30-min interval indicates that estimates for 95% of all subjects recorded at 30-min intervals differed by less than 20% of the workday (9.75×1.96) from the 5-min values. At 15 min, short-term tasks are not likely to be missed, and the resulting percent workday estimates for these tasks will be closer to the true percentage of the sample period that the task occupied. The drawback to decreasing the observation interval to 15 min is that the workload on the rater is increased, and the rater must remain close to the work area for the sample period. Given this, it is appropriate to conclude that while a 30-min interval is short enough to characterize construction work for most heavy and highway construction activities, a 15-min interval provides substantial improvements in the precision of potential exposure determinants.

CONCLUSIONS

Due to the dynamic nature of the construction environment and the corresponding variability in factors affecting particulate exposures, a method was developed to quantify the determinants of exposure to particulate matter that tend to vary through the day. TVEA uses a work-sampling based strategy to estimate the percent of the workday that exposure determinants occurred.

Results from the data analysis suggest that the inter-rater reliability for TVEA was acceptable. Most of the TVEA exposure determinants showed substantial to almost perfect agreement between raters. Exposure determinants related to diesel exhaust proved the most difficult type of particulate matter for raters to agree on. Observation of the occurrence of exposures suggested that particulate exposures occurred at essentially random intervals through the sample period, indicating that fixed intervals for work sampling were appropriate. The observation interval of 30 min, while reasonable in terms of the estimates of potential exposure determinants it provides for the user, should be replaced with a shorter interval of 15 min between observations to assure that exposure determinant estimates will differ by less than 10% from the "true" percent of the workday, and rare events will not be missed or overestimated. One advantage of TVEA is that it is flexible in that only those exposure determinants that are of interest need be coded, and the coding interval can be adjusted to accommodate the level of accuracy desired.

This study has shown that TVEA is a useful exposure assessment tool for the dynamic construction environment. The study described here focused largely on laborers who are challenging to rate with TVEA because their work tends to vary more than some of the other construction trades. The success of TVEA with this challenging group suggests that it would be successful in other heavy and highway operations not yet studied, with other trades, and, we believe, even in other types of construction such as commercial and residential building.

Although the raters used in the reliability study were occupational health and safety professionals, the method requires only that someone have familiarity with the equipment and tools used in construction. Other exposure assessment approaches in construction have successfully used union workers to collect data.[6] TVEA could also be used as part of a participatory exposure assessment strategy.

ACKNOWLEDGMENTS

Thanks to the contractors, construction workers, and local unions who participated in the sampling, and to the students and staff who assisted in data collection and analysis: Abbas Virji, Nicole Blute, Rebecca Gore, Dana Hanson, and Heather Lyons. Also, thanks to Pam Susi and Jim Platner from CPWR for their assistance and support.

This publication was supported by grant number CCU317202 from the National Institute of Occupational Safety and Health (NIOSH) of the Centers for Disease Control and Prevention in cooperation with the Center to Protect Workers' Rights.

REFERENCES

1. **Woskie, S.R., A. Kalil, D. Bello, and M.A. Virji:** Exposures to quartz, diesel, dust and welding fumes in heavy and highway construction. *Am. Ind. Hyg. Assoc. J. 63*:447–457 (2002).
2. **Ringen, K., A. Englund, L. Welch, J.L. Weeks, and J.L. Seegal:** Why construction is different. *Occup. Med. 10:*255–260 (1995).
3. **Susi P., and S. Schneider:** Database needs for a task-based exposure assessment model for construction. *Appl. Occup. Environ. Hyg. 10*:394–399 (1995).
4. **Goldberg, M., S.M. Levin, J.T. Doucette, and G. Griffin:** A task-based approach to assessing lead exposure among iron workers engaged in bridge rehabilitation. *Am. J. Ind. Med. 31:*310–318 (1997).
5. **Susi, P., M. Goldberg, P. Barnes, and E. Stafford:** The use of a task-based exposure assessment model (T-beam) for assessment of metal fume exposures during welding and thermal cutting. *Appl. Occup. Environ. Hyg. 15*:26–38 (2000).
6. **Pape, E.S.:** Work sampling. In *Handbook of Industrial Engineering*, 2nd Edition. G. Salvendy (ed.). New York: John Wiley & Sons, 1991.
7. **Hansen, D.J., and L.W. Whitehead:** The influence of task and location on solvent exposures in a printing plant. *Am. Ind. Hyg. Assoc. J. 49*:259–265 (1988).
8. **Buchholz, B., V. Paquet, L. Punnett, et al.:** PATH: A work sampling based approach to ergonomic job analysis for construction and other non-repetitive work. *Appl. Ergon. 27*:177–187 (1996).
9. **Brantley, C.D., and P.C. Reist:** Abrasive blasting with quartz sand: Factors affecting the potential for incidental exposure to respirable silica. *Am. Ind. Hyg Assoc. J. 55*:946–952 (1994).
10. **Cohen, J.:** A coefficient of agreement for nominal scales. *Educ. Psychol. Meas. 20*:37–46 (1960).
11. **Fleiss, J.L.:** *Statistical Methods for Rates and Proportions*, 2nd Edition. New York: John Wiley & Sons, 1981.
12. **Landis, J.R., and G.G. Koch:** The measurement of observer agreement for categorical data. *Biometrics 33*:159–174 (1977).
13. **Westgard, J.O., and M.R. Hunt:** Use and interpretation of common statistical tests in method-comparison studies. *Clin. Chem. 19*:49–57 (1973).
14. **Siemiatycki, J., L. Fritschi, L. Nadon, and M. Gérin:** Reliability of an expert rating procedure for retrospective assessment of occupational exposure in community-based case control studies. *Am. J. Ind. Med. 31*:280–286 (1997).