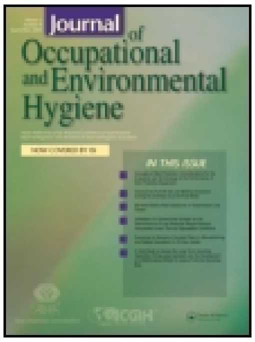

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# Comparison of Task-Based Exposure Metrics for an Epidemiologic Study of Isocyanate Inhalation Exposures Among Autobody Shop Workers

**Susan R. Woskie,[1] Dhimiter Bello,[1] Rebecca J. Gore,[1] Meredith H. Stowe[2], Ellen A. Eisen[1,4] Youcheng Liu,[2,3] Judy A. Sparer,[2] Carrie A. Redlich,[2] and Mark R. Cullen[2]**

[1]Department of Work Environment, University of Massachusetts at Lowell, Lowell, Massachusetts
[2]Occupational Medicine, Yale University, New Haven, Connecticut
[3]Department of Preventive Medicine and Environmental Health, University of Kentucky, Lexington, Kentucky
[4]Environmental Health Sciences, University of California Berkeley, Berkeley, California

*Because many occupational epidemiologic studies use exposure surrogates rather than quantitative exposure metrics, the UMass Lowell and Yale study of autobody shop workers provided an opportunity to evaluate the relative utility of surrogates and quantitative exposure metrics in an exposure response analysis of cross-week change in respiratory function. A task-based exposure assessment was used to develop several metrics of inhalation exposure to isocyanates. The metrics included the surrogates, job title, counts of spray painting events during the day, counts of spray and bystander exposure events, and a quantitative exposure metric that incorporated exposure determinant models based on task sampling and a personal workplace protection factor for respirator use, combined with a daily task checklist. The result of the quantitative exposure algorithm was an estimate of the daily time-weighted average respirator-corrected total NCO exposure ($\mu g/m^3$). In general, these four metrics were found to be variable in agreement using measures such as weighted kappa and Spearman correlation. A logistic model for 10% drop in $FEV_1$ from Monday morning to Thursday morning was used to evaluate the utility of each exposure metric. The quantitative exposure metric was the most favorable, producing the best model fit, as well as the greatest strength and magnitude of association. This finding supports the reports of others that reducing exposure misclassification can improve risk estimates that otherwise would be biased toward the null. Although detailed and quantitative exposure assessment can be more time consuming and costly, it can improve exposure-disease evaluations and is more useful for risk assessment purposes. The task-based exposure modeling method successfully produced estimates of daily time-weighted average exposures in the complex and changing autobody shop work environment. The ambient TWA exposures of all of the office workers and technicians and 57% of the painters were found to be below the current U.K. Health and Safety Executive occupational exposure limit (OEL) for total NCO of 20 $\mu g/m^3$. When respirator use was incorporated, all personal daily exposures were below the U.K. OEL.*

**Keywords** autobody shop, exposure assessment, isocyanate, occupational epidemiology, task-based

Address correspondence to Susan Woskie, University of Massachusetts at Lowell, Department of Work Environment, One University Avenue, Lowell, MA 01854; e-mail: susan_woskie@uml.edu.

## INTRODUCTION

Despite the strides made in the field of exposure assessment for occupational epidemiologic studies, most studies use surrogates of exposure, rather than quantitative measures in their analysis.[(1)] Nevertheless, in those few studies that have evaluated the question, quantitative exposure measures have been shown to improve the analysis of exposure-response relationships.[(2,3)]

As part of a series of epidemiologic studies of the respiratory, immunological, and physiological responses to isocyanate exposures among autobody shop workers, a detailed exposure assessment was performed, including analytical methods development,[(4,5)] air sampling and exposure modeling,[(6,7)] dermal exposure assessment,[(8,9)] and respiratory protection evaluation.[(10)] This article describes the development of a quantitative metric of inhalation exposures among current autobody workers and compares it with other less specific surrogates of exposure, including job title.

Isocyanates have been identified as a major cause of occupational asthma in industrialized countries, with 1–20% of exposed workers developing occupational asthma.[(11,12)] The autobody industry uses isocyanates in primer, base (pigmented color), and clear coatings. Although at one time these coatings contained substantial amounts of isocyanate monomer, now they are largely combinations of polyisocyanates,[6,13] which are also capable of causing asthma.[14–16]

## METHODS

In the United States, autobody shops are small businesses with a median employment of five workers, including the owner. Each shop is physically different and each day the work to be done by the workers differs, since each vehicle can require a range of tasks to repair and refinish it. In addition to difficulties in defining a "typical day," monitoring isocyanates is complicated due to the nature of the exposure: different isocyanate types are used, including hexamethylene diisocyanate (HDI)-based and isophorone diisocyanate (IPDI)-based coatings; several of these isocyanate components are present as both monomers and polyisocyanates and the isocyanate exposures are commonly a mixture of vapors and aerosols.[6]

### Tiers of Exposure Algorithm

Due to the complexity of the work patterns in the autobody industry, the exposure assessment methodology for autobody shop workers focused on use of a daily task checklist during the week when intensive medical evaluations were being done (cross-day and cross-week respiratory function measurement, cross-week methacholine challenge testing, collection of respiratory symptom reports, and immunologic testing). The daily task checklist was collected for each worker during each day (Monday through Thursday) in the shop. Industrial hygiene technicians used the checklist to indicate every half-hour which tasks a worker had participated in and which type of personal protective equipment was used, if any. In addition, the checklist was used to indicate whether a worker had potential bystander exposure because they had been working nearby when another worker sprayed an isocyanate coating outside a spray booth. This usually involved spraying of primer or sealer on smaller areas of a car.

These daily task checklists formed the backbone of a tiered exposure assessment strategy (Figure 1). To start, each worker was assigned to a job category based on a self-reported job title. Tier 1 of the exposure assessment strategy was to count "iso spray events," defined as any task conducted by the worker that involved spraying isocyanate containing coatings. Tier 2 tried to account for bystander exposures during spraying operations done outside the spray booth on the shop floor[8] by counting as iso events both spray tasks conducted by the worker (Tier 1) and near spray events (potential bystander exposure from nearby spraying by other workers). Tiers 1 and 2 represent an exposure surrogate approach that could be given to workers in a questionnaire format for exposure assessment purposes.

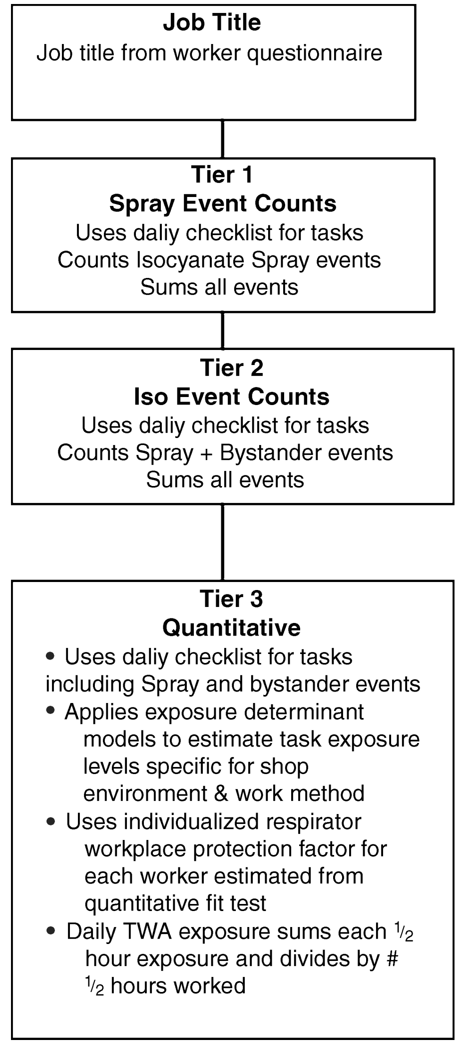


**FIGURE 1.** Exposure metrics

### Quantitative Algorithm (Tier 3)

The third tier was the quantitative exposure assessment based on the exposure determinant models developed from the sampling results collected during the study.[7] It included a personal workplace protection factor estimated using each worker's quantitative fit testing result.[10] For this tier, the tasks listed in each 30-min period were assigned to one of several categories: Spray (counts of task used in Tiers 1 and 2), Near Spray (bystander events) (counts used in Tier 2), Mixing, Sanding (dry), or Shop Background (Table I).

Previously, task level exposure determinant models were developed based on 380 task-based personal measurements of HDI-based monomer and polyisocyanate and isophorone diisocyanate (IPDI)-based polyisocyanate that were collected from 33 autobody shops.[7] This study uses these previously identified statistically significant predictors of task level exposures to estimate the task exposure during each half-hour

**TABLE I. Main Diary Tasks in Autobody Shops**

| Task Grouping | Tasks Within Each Group | Assignment for Tier 3 Quantitative Algorithm |
|---|---|---|
| Structural repair | Mechanical work/frame and sheet metal straightening/cutting and grinding and welding | Shop Background |
| Bondo work | Bondo/sanding bondo | Shop Background |
| Preparation for spray | Paint mixing/clean up paint equipment | Mixing |
| Spraying | Spray application of primer, sealer, base coat (usually not isocyanate containing), clear coat either inside spray booth or outside spray booth on shop floor. | Spray<br>Separate info on (in spray booth or out of booth job) (clear coat vs. primer/sealer sprayed) |
| Spray bystander | Bystander exposure of worker near spraying operation done outside spray booth on shop floor | Near Spray |
| Sanding | Dry sanding of primer or other isocyanate containing coatings | Sanding |
| Untaping | Untaping | Shop Background |
| Finish, cosmetics | Buffing/compounding/polishing/glazing/ wet sanding | Shop Background |
| Miscellaneous | Car washing, cleaning, taping, shop cleaning, moving cars, restocking supplies | Shop Background |
| Office work | Office work, shop management and medical tests for study, shop meeting | Shop Background |
| Lunch/break | Lunch/break | Shop Background |

period of each subject's workday by taking into account their specific worksite and process characteristics.

- For Spraying tasks, if the task was outside a spray paint booth, the statistically significant predictors included milliliters (mL) of NCO applied (↑ exposure); and the size of the shop (> 5000 feet$^2$ or 465 m$^2$)(↑ exposure).
- If the spraying was inside a booth, the statistically significant determinants included the type of spray booth (custom crossdraft ↑↑ exposure, prefabricated crossdraft ↑ exposure, both relative to downdraft booth); mL of NCO applied (↑ exposure); and the number of gallons (3.78 L/gallon) of clear coat used by the shop per month (↓ exposure). A shop with a higher clearcoat application volume was generally a larger, more spacious shop with more modern equipment and better maintenance, all of which result in lower exposures.
- For intervals where the worker had a Near Spray (bystander) exposure, the statistically significant predictors included outdoor temperature ≤65°F (18.3°C) (↑ exposure); and shop size >5000 ft$^2$(↓ exposure).
- For Mixing, there were no statistically significant determinants so the median value for the task was assigned to each 30-min interval where this task occurred.
- For Sanding, a logistic model was used where the statistically significant exposure determinants predicted the probability of NCO exposures being above the 80th percentile of the exposure distribution during sanding. If the sanding was done when the average outdoor temperature for the week was ≤65°F, the median value for all the exposures above the 80th percentile was assigned. If the temperature was >65°F then the median value for all the exposures below the 80th percentile was used.
- For Shop Background tasks (Table I), a logistic model was used, where the statistically significant exposure determinants predicted the probability of NCO levels being above the 80th percentile of the exposure distribution of NCO exposures. If the shop annual income was ≤$600,000, the median value for all the exposures above the 80th percentile was assigned for all Shop Background tasks. If the shop income was >$600,000, then the median value for all the exposures below the 80th percentile was assigned as the Shop Background level for tasks that did not involve isocyanate use.

For tasks where a respirator was worn, the exposure predicted by the determinant models was divided by a workplace protection factor (WPF). Most commonly used was the half-facepiece disposable or reusable cartridge respirator with charcoal cartridges and N95 (or P95) prefilter (86% of shops). Supplied-air respirators were used by painters in 30% of the shops.[6] For the half-facepiece cartridge respirators, individual workplace protection factors are predicted from workers' personal quantitative fit factors measured with the

**TABLE II. Exposure Metrics**

| (n = 893 days) | Median (10–90th Percentile) (max) Office Work (n = 245 days) | Technician (n = 458 days) | Painter (n = 190 days) |
|---|---|---|---|
| Tier 1: Daily Spray Counts | 0 (0–0) [2] | 0 (0-1) [2] | 2(0–6) [12] |
| Tier 2: Daily Iso Event Counts | 0 (0–0) [4] | 0 (0–2) [6] | 3 (0–7) [14] |
| Ambient Daily TWA ($\mu$g NCO/m$^3$) (from algorithm) | 0.02 (0.01–0.38) [19.57] | 0.17 (0.02–1.64) [15.38] | 7.99 (0.03–20.26) [43.43] |
| Tier 3: Quantitative Metric ($\mu$g NCO/m$^3$) (Respirator-Corrected Ambient Daily TWA) | 0.02 (0.01–0.38) [3.85] | 0.08 (0.01–0.76) [7.83] | 0.30 (0.02–2.10 [15.63] |

TSI PortaCount respirator fit tester (Shoreview, Minn.).(10) For supplied-air respirators, a WPF of 1000 was used based on assigned protection factors in OSHA's revised Respiratory Protection Standard,(17) since the authors could not use the quantitative fit testing to individualize the WPF.

Because task data was collected in half-hour intervals throughout the day, exposure was estimated for each half-hour interval using the exposure determinant models to predict the total NCO mass collected during task sampling, and the air concentration for that half hour interval was estimated by dividing by 0.06 m$^3$ (the air volume collected at 2 l/min for 30 minutes). Respirator correction was applied if the checklist indicated that a respirator was used during that task. The estimated respirator-corrected TWA air concentrations (total NCO $\mu$g/m$^3$) for the day was calculated by summing the concentration during each half-hour interval and dividing by the number of half-hour intervals worked in the day. A non-respirator-corrected TWA air concentration for each day was also calculated for use in comparing with occupational exposure limits and previous studies (Table II). A linear regression model with job and subject nested in job as random effects was used to partition the exposure variability for the ambient and respirator corrected quantitative exposure estimates (total NCO $\mu$g/m$^3$).

### Comparison of Algorithms

One way to evaluate the utility of the different algorithm tiers is to use them in an exposure-response model to examine cross-week change in FEV$_1$ for the 232 subjects in the study (64 office workers, 118 technicians, 49 painters). A logistic model was used to examine the odds of a greater than 10% drop in FEV$_1$ from Monday morning to Thursday morning as the outcome. The demographics of the cohort of 232 autobody workers and the general the respiratory function testing results are described elsewhere.(16) The study had approval from the Yale and University of Massachusetts institutional review boards. The final model for predicting the likelihood of a drop in FEV$_1$ across the week included covariates for worker age, smoker (yes/no), ethnicity (Hispanic or other; primarily Caucasian but also a small number of African Americans), and the responsiveness to methacholine challenge on Monday morning. Methacholine responsiveness was considered positive if the methacholine concentration required for a 20% drop in FEV$_1$ was less than 16 mg/mL.

For each potential exposure metric a 3-day average exposure (Monday to Wednesday) was calculated to match with the Monday morning to Thursday morning FEV$_1$ measurements. Since the metrics produced by each algorithm are on different scales, odds ratios were also calculated for the 10–90th percentile range of each tier's exposure metric for painters: OR = $e^{(\beta \Delta x)}$ where $\Delta$ = parameter estimate for exposure metric from the logistic model and $\Delta$x = the 10–90th percentile range for metric.

In addition to the exposure response model, other approaches such as correlation and agreement were used to compare the various metrics. With the exception of the job title, all algorithm tiers produced an ordinal estimate. Therefore, Spearman correlations were used to compare the estimates produced for each subject's 3-day average by each method. The ordinal estimates were not normally distributed within a job title, so comparisons between job titles were done using a nonparametric Kruskal-Wallis Chi square on the Wilcoxon rank sum scores. In addition, ordinal levels from each algorithm tier were categorized into low, medium, or high using two methods.

The first method was to plot the distribution of counts greater than zero or the natural log of the respirator-corrected TWA air concentrations and determining the natural cut points in the distribution. For the spray counts and iso event counts, low was zero counts; medium 1–3 counts, and high greater than or equal to 4 counts. For the respirator-corrected TWA air concentrations, low as less than 0.05 $\mu$g NCO/m$^3$, medium as >0.05–0.7 $\mu$g/m$^3$, and high as > 0.7 $\mu$g/m3. Using 3 × 3 frequency table of job title vs. low, medium, high exposure, the percentage of subjects falling on the diagonal (agreement) and the weighted kappa statistic were calculated for each tier In the second method for developing the high, medium, and low categories the 232 subjects' 3-day average exposures were sorted from lowest to highest. The lowest 28% measurements were categorized as low (based on 64/232 subjects being office workers), the next 51% were called medium (based on 118/232 subjects being technicians), and the top 21% measurements were identified as high (based on 49/232 subjects being painters).

## RESULTS

Algorithm metrics for each tier were calculated for 232 workers: 65 office workers, 49 painters, and 118 technicians from 33 autobody shops. Each worker was sampled on 3 to 4 days, resulting in 893 person-days for exposure estimation. Statistics for the metrics produced by each algorithm tier are described for all the daily exposures (Table II). All jobs have a minimum exposure of 0, since each job had workers who never sprayed isocyanate-based paints during the week of observation, including 12% of the painters.

A nested random effects model for job and subject showed that for ambient levels 55% of the exposure variability was between job categories, 24% was between subjects in a job category, and 21% was within-subject (day-to-day) variability in exposure. However, for the respirator-corrected TWA exposures, 85% of the variability was within-subject (day-to-day) variability, while only 9% of the variability was between job categories and 6% was between subjects within a job category. These models could not be run on the Tier 1 or Tier 2 count data because of the high number of zero values.

### Tier 1 Algorithm: Isocyanate Spray Counts

Use of the Tier 1 algorithm found that job titles were significantly different from each other according to the nonparametric Chi-Square test (Table III). However, examination of box plots of iso event counts by job title showed overlap between all job titles (Figure 2). Although the median number of spray events for office workers and technicians was zero (Table II), 31% of the technicians sprayed at least one time during the week of observation. Two percent of the office workers sprayed at least one time during the week of observation. Twelve percent of the painters did not spray any isocyanate-based paints at all during the week of observation. The spray event counts for each person-day were stratified into low, medium, and high and tabulated against job title (presuming office workers are low, technicians medium and painters high in potential exposure) (Table III).

There was better agreement (91%) when the high, medium, and low categories were determined by sorting the 232 subjects 3-day average number of spray events from lowest to highest and assigning the lowest 28% measurements to the low category, the next 51% to the medium category, and the top 21% to the high category (as described in the methods). When using the natural cut point approach for determining high, medium, and low exposure categories the agreement was only 48% (Table III). With the natural cut point approach, 72% of the technicians were "misclassified" as "low" but none as "high," whereas with the sequential sorting approach 8% of the technicians were misclassified as high. With the natural cut point approach, 69% of the painters were misclassified as low or medium, whereas with the sequential sorting approach only 18% were misclassified as medium.

### Tier 2 Algorithm: Isocyanate Event Counts

Use of the Tier 2 algorithm to calculate the isocyanate event count metric found job titles were significantly different from each other according to the nonparametric Chi-Square test (Table III). However, examination of box plots of iso event counts by job title showed overlap between all job titles (Figure 3). The iso event counts for each person-day were stratified into low, medium, and high and tabulated against job title (Table III). There was good agreement (82%) when the high, medium, and low categories were determined by sorting the 232 subjects' 3-day average number of spray events from lowest to highest and apportioning the subjects according to the percentage of office workers, technicians, and painters (see Methods section).

When using the natural cut point approach for determining high, medium, and low exposure categories the agreement was only 58% (Table III). As with the spray counts, the natural cut point approach "misclassifies" more subjects as "low"

**TABLE III. Comparison of Metrics**

| | Comparison by Job Category[A] | | | Spearman Correlation | | |
|---|---|---|---|---|---|---|
| | Nonparametric Chi-Square Test[B] | Kappa and % Agreement Using Natural Cut Points of Exposure[C] | Kappa and % Agreement Using Exposure Order Cut Points[D] | Tier 1 Spray Event Counts | Tier 2 Iso Event Counts | Tier 3 Quantitative Metric |
| Tier 1 Spray Event Counts | 120.47 ($p < 0.0001$) | 0.34 (48%) | 0.88 (91%) | 1.0 | 0.86 | 0.50 |
| Tier 2 Iso Event Counts | 104.49 ($p < 0.0001$) | 0.44 (58%) | 0.75 (82%) | 0.86 | 1.0 | 0.57 |
| Tier 3 Quantitative Metric | 37.46 ($p < 0.0001$) | 0.31 (54%) | 0.32 (53%) | 0.50 | 0.57 | 1.0 |

[A] Job category: Office Work, Technician, Painter.
[B] Nonparametric chi-square test on Wilcoxon scores by job category.
[C] Weighted kappa using natural cutpoints from histograms to determine high, medium, and low categories of exposure metrics for comparison with job categories.
[D] Weighted kappa using job categories compared with exposure categories determined by sorting 232 subjects 3-day average exposures lowest to highest. Lowest 28% measurements = low (64/232 office workers), next 51% (118/232 technicians) as medium, and top 21% (49/232 painters) as high.

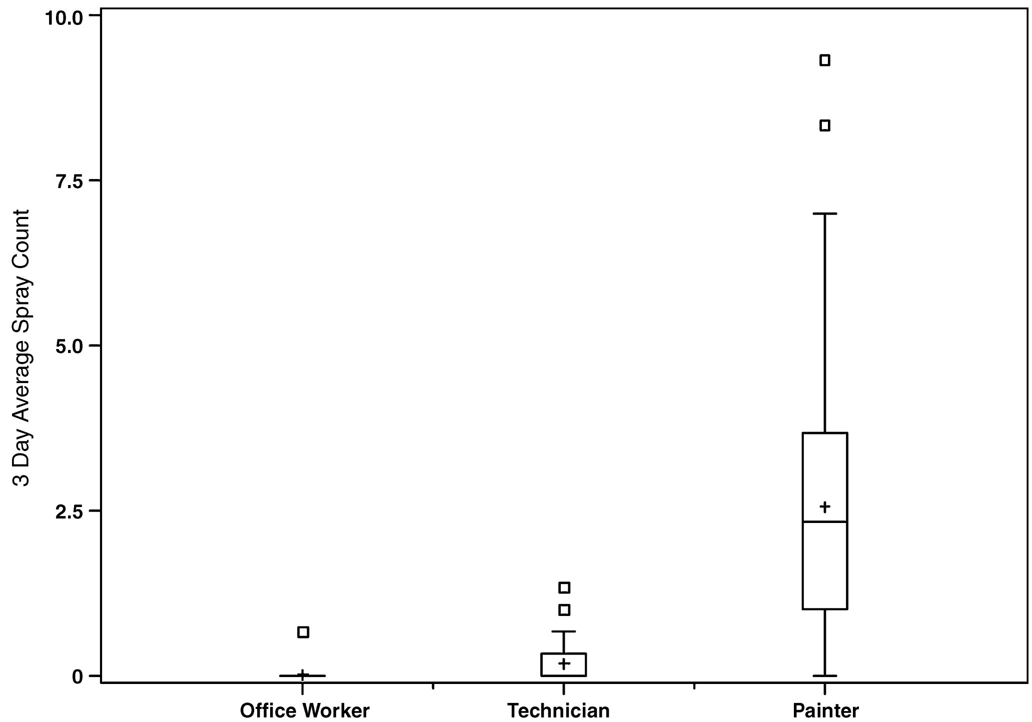


**FIGURE 2.** Distribution of Tier 1 worker 3-day average spray event counts by job title. The box shows the 25th and 75th percentile of the distribution (interquartile range). The mean is represented with a cross and the median with a bar across the box. The whiskers illustrate the maximum and minimum values within the upper and lower fences (1.5 times the interquartile range) respectively. The points beyond the whiskers are outside the fences and represent outliers.

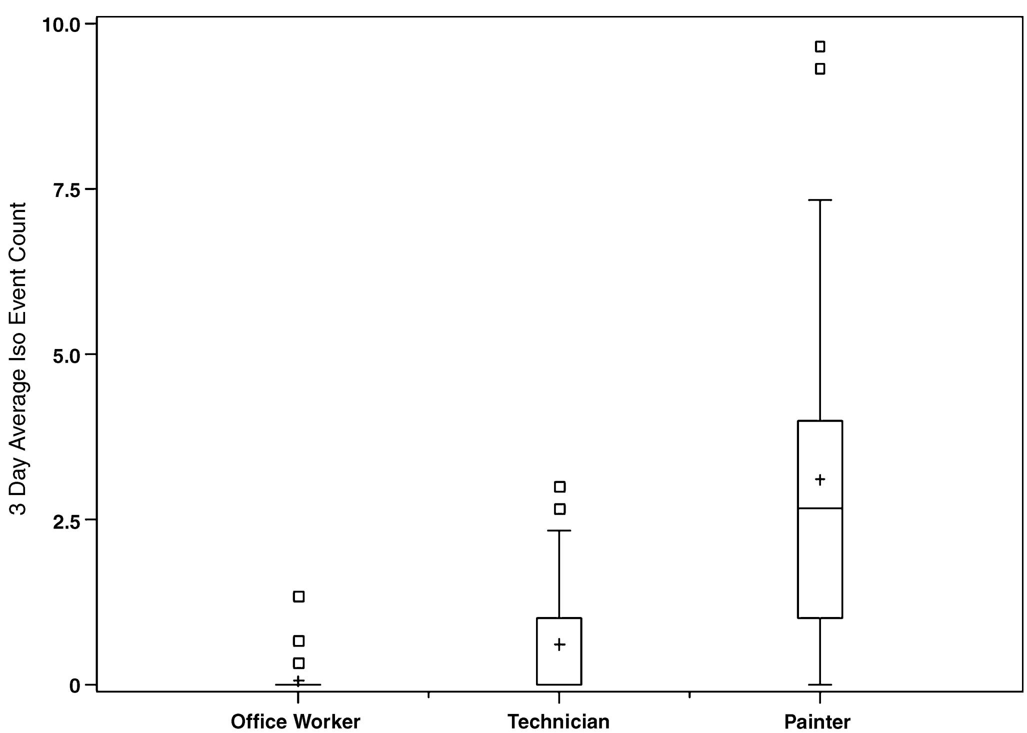


**FIGURE 3.** Distribution of Tier 2 worker 3-day average isocyanate event counts by job title

but none as "high," whereas the sequential sorting approach misclassifies 14% of the technicians as high. On the other hand, 59% of the painters were misclassified as low or medium with the natural cut point approach, whereas with the sequential sorting approach only 34% of the painters were misclassified and all as medium.

### Tier 3 Algorithm: Quantitative Exposure

The quantitative exposure metric produced exposures that were significantly different from each other according to the nonparametric Chi-Square test (Table III). However, examination of box plots of the weekly average of the daily average total $\mu$g NCO/m$^3$ by job title showed overlap between all job titles (Figure 4). The daily average total $\mu$g NCO/m$^3$ for each person-day was stratified into low, medium, and high and tabulated against job title (Table III).

There was about the same agreement between job title and exposure categories whether the exposure sorting or the natural cut point approach was used for determining high, medium, and low exposure categories (54% vs. 53%) (Table III). The natural cut point approach "misclassified" 30% of the office workers as medium and 2% as high, whereas the sorting approach misclassified 42% as medium and 8% as high. For technicians the natural cut point approach misclassified 39% as low and 5% as high (44% total), whereas the sorting approach misclassified fewer as low (25%) but more as high (17%) (42% total). For painters, the natural cut point misclassified more subjects in both the low and medium categories (69% total), whereas the sorting approach misclassified a total of 51% in both low and medium categories.

### Comparison of Metrics to each other

Regardless of the categorization method, from Tier 1 spray counts to Tier 2 iso event counts there is an increasing agreement with the job category. (Table III) However, agreement for Tier 3, the quantitative algorithm that estimates daily average total $\mu$g NCO/m$^3$ exposure level, is reduced (Table III). Spearman correlation for the 3-day average spray event counts vs. the 3-day average iso event counts was 0.86; however correlation of the 3-day average estimated daily respirator-corrected total $\mu$g NCO concentration with spray events and iso events was 0.50 and 0.57, respectively. Thus, the question arose as to whether this reduced agreement for the quantitative metric is a reflection of a more refined exposure estimate or increased misclassification.

To examine the basis for the difference in the counts and the quantitative algorithm, spray counts vs. respirator-corrected daily average total $\mu$g NCO/m$^3$were plotted with the points identified by whether the person wore a respirator more or less than 50% of the time when spraying isocyanate containing paints (Figure 5).

Workers with many spray events per day tend to wear respiratory protection more than 50% of the time and have lower $\mu$g NCO/m$^3$ exposures, whereas those with few spray

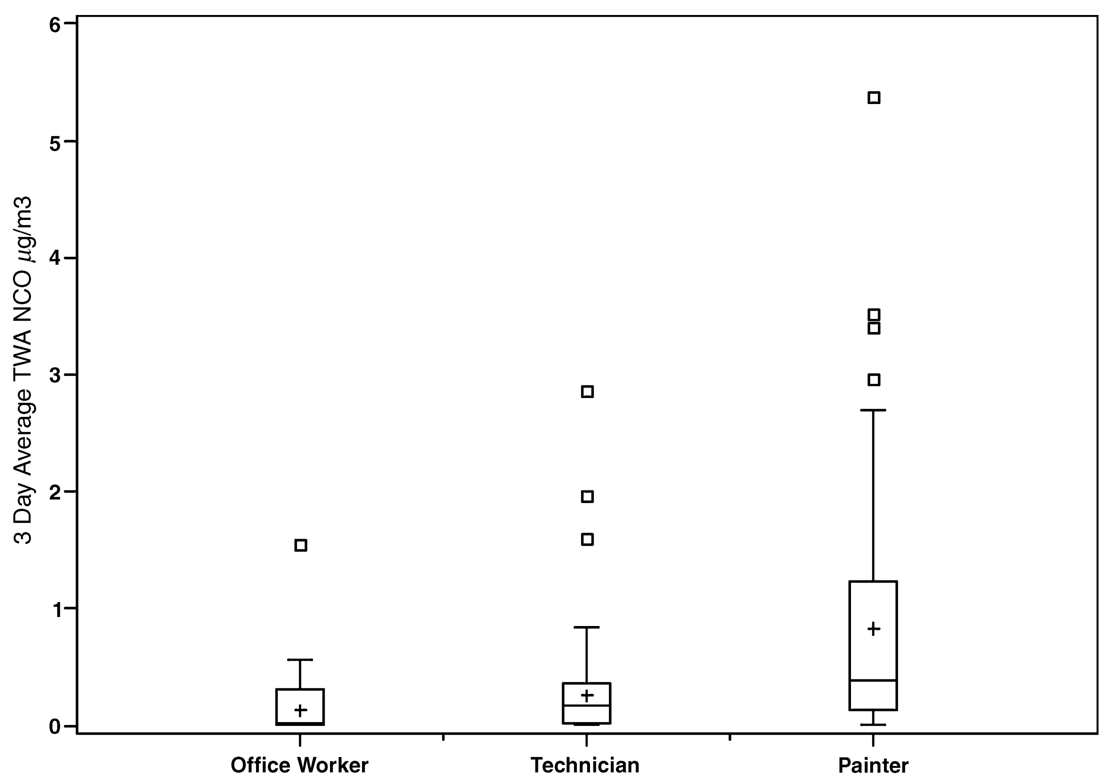


**FIGURE 4.** Distribution of Tier 3 worker 3-day average TWA total NCO $\mu$g/m$^3$ exposure by job title

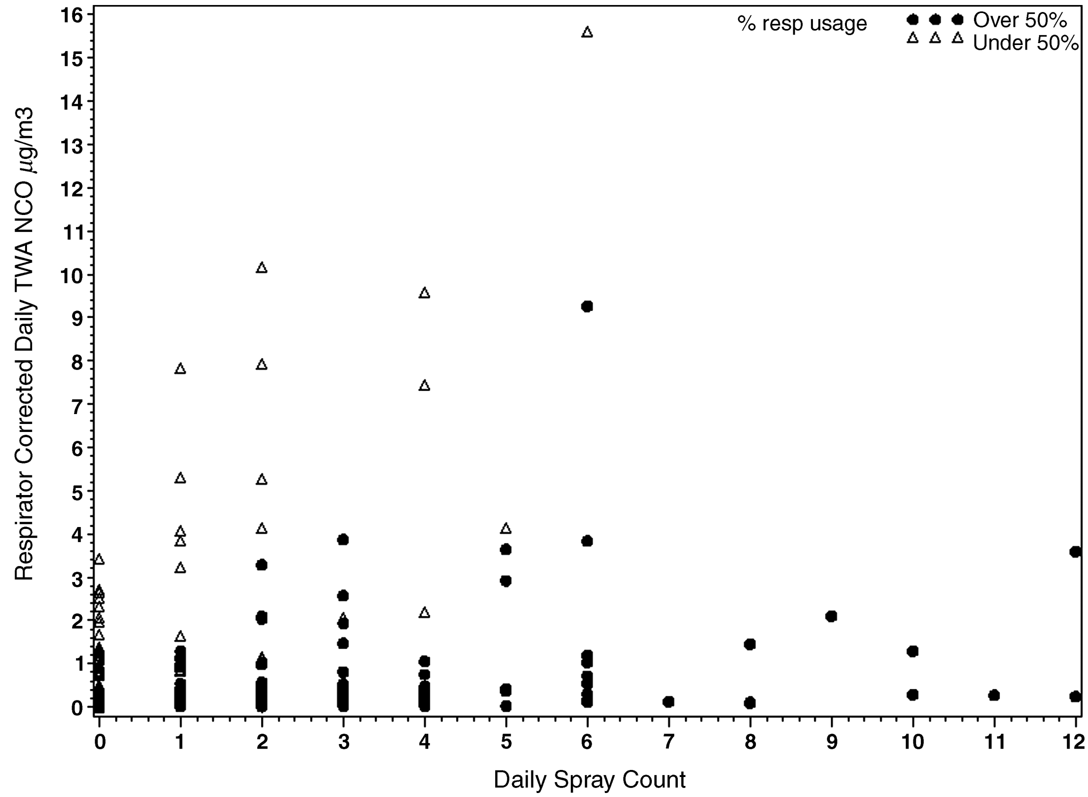


**FIGURE 5.** Plot of Tier 3 quantitative algorithm worker daily TWA total NCO $\mu$g/m$^3$ exposure estimates vs. daily spray event count

events tended not to wear their respiratory protection, resulting in high daily exposure levels. Also, as expected, workers with the same number of spray counts but who use respiratory protection have a lower quantitative exposure estimate. This interpretation is supported by the observation that regardless of the method of categorizing high, medium and low quantitative exposures, the high exposure category contains a substantial number of non-painters (32–51%). This is likely due to the fact that at least 30% of the painters, 10% of the technicians and 2% of the office workers sprayed at least once without a respirator.

For those who wear respirators, daily spray count does not appear to increase exposure (Figure 5). This may reflect the countervailing influence of busier shops with more paint jobs being more likely to have the more protective downdraft spray booths and/or use airline respirators when spraying.

### Use of Metrics in Exposure Response Analysis

The models using the four tiers of exposure metrics can be compared in several ways (Table IV). First is the strength of the association of exposure with the health outcome. With this approach the p value for the exposure parameter estimate in the model is best for the Tier 3 quantitative algorithm followed by the job title. Another approach would be to examine the model fit. Here the Tier 3 quantitative algorithm is again the best fit (smallest -2 log likelihood and Aiken Information Criterion) followed by the job title.

Finally, the magnitude of the association may be another way to evaluate the exposure metrics. However, it is difficult to compare the odds of having a 10% drop in $FEV_1$ with a unit increase in exposure if the metrics are all in different scales when continuous (spray counts, iso event counts, respirator-adjusted daily TWA $\mu$g NCO/m$^3$) or are categorical (job title). To try to make these comparisons more comparable, especially with the categorical analysis by job title, the 10–90 percentile range of each continuous variable for the painters was used to estimate a second odds ratio for each metric. The odds ratio for the Tier 3 quantitative metric is then comparable to that of the categorical painter odds ratio in the job title analysis.

## DISCUSSION

The selection of the best exposure metric for an occupational epidemiologic study has received little attention, since many studies are restricted to only one metric at best. However, in studies where there is more than one exposure metric possible, the issue of how to compare has yet to be resolved. In some cases, choosing a metric based on the maximum effect estimate will result in a different decision than one where the overall best model fit is the criterion.[18] In this study, Tier 3, the quantitative exposure metric, was

**TABLE IV. Results of Exposure-Response Logistic Models with Alternative Exposure Metrics**

| | Odds Ratio | P Value | OR 95% Confidence Interval | −2 Log Likelihood (AIC)[A] | Odds Ratio for 10–90th Percentile of Exposure for Painters |
|---|---|---|---|---|---|
| Job title | | | | | |
| Painter | 8.30 | 0.06 | 0.96–72.10 | 116.3 (130.3) | — |
| Technician | 5.67 | 0.10 | 0.70–45.87 | | |
| Office worker | 1.00 | — | — | | |
| Tier 1 | | | | | |
| 3-Day average spray counts | 1.11 | 0.47 | 0.84–1.46 | 121.6 (133.6) | 1.66 |
| Tier 2 | | | | | |
| 3-Day average iso event counts | 1.02 | 0.85 | 0.79–1.33 | 122.0 (134.0) | 1.19 |
| Tier 3 | | | | | |
| 3-Day average daily TWA $\mu$g NCO/m$^3$ | 2.14 | 0.003 | 1.29–3.54 | 113.5 (125.5) | 7.65 |

*Note:* Logistic models include age, smoking status (current or other), race (Hispanic or other), methacholine responsiveness (0/1 for 20% drop in FEV1 at <16 mg/mL methacholine).
[A] AIC, Aiken Information Criterion.

the best index based on model fit as well as strength and magnitude of the association. Use of Tier 1 and 2 metrics produced misclassification relative to job title and relative to the Tier 3 quantitative exposure metric.

Others have shown that when there is nondifferential exposure classification in all directions, risk estimates are underestimated toward the null value.[(19)] This further supports the finding that the strength and magnitude of the exposure response relationship was stronger for the Tier 3 quantitative exposure metric than for any of the other metrics. It is not clear why job title is a better exposure index than the Tier 1 spray counts or Tier 2 iso event counts, unless it is that the job title is a surrogate for exposure not accounted for in the count data, such as dermal exposure. However, when comparing categorized Tier 1 and 2 metrics to job categories the agreement was 48–91% (Table III), suggesting that these metrics did differentiate jobs even though they did not account for respirator use. The impact of different methods of categorizing exposure has been examined previously, mostly in the context of the impact on risk estimates.[(18,20)]

Although use of the quantitative exposure metric (Tier 3) produced the most favorable exposure response model, it has the additional benefit of providing data on the relationship between the workplace intensity of exposure and health risks that can be used in the development of regulatory initiatives and control strategies. Thus, the increased cost of a full quantitative exposure assessment is offset by the potential reduction in exposure misclassification and the greater utility of study results for policy and prevention initiatives.

The task-based approach used here to estimate quantitative exposures has not been commonly used in epidemiologic studies. However, use of a task-based approach has several advantages: (1) it addresses the components of highly variable jobs separately (exposure level and time);[(21,22)] (2) it can make historical estimation easier by separating out changes in task level from changes in task time;[(23,24)] (3) it lends itself to exposure interventions focused on the task and time that contribute most to daily exposures;[(25)] (4) it allows daily "peak" exposures to be monitored.[(26)]

Aliphatic monomer and polyisocyanate concentrations during spray painting in autobody shops have been reported for several studies during the past 15 years. However, most of those studies have focused on measurement of air concentrations during the spray painting task itself, with few samples taken during other tasks. A summary of previous isocyanate autobody sampling studies, converted to a $\mu$g NCO/m$^3$ metric is reported in a companion paper.[(6)]

To the authors' knowledge, only the Swedish epidemiologic studies of car painters have reported daily time-weighted average (TWA) exposures to HDI monomer and HDI polyisocyanate. These studies combined air concentrations and work time in three tasks (painting 10% of the day, mixing 13% of the day, and work in other areas 77% of the day). Painting levels varied depending on booth ventilation categories.

In addition, exposures were adjusted for the use of respirators based on interview. The resulting daily average exposures were reported as mean of 115 $\mu$g/m$^3$ HDI-biuret polyisocyanate (25$\mu$g/m$^3$ total NCO)[(27)] and 90 $\mu$g/m$^3$ HDI-biuret polyisocyanate (20 $\mu$g/m$^3$ total NCO)[(28)] for the car painters. In the study reported by Alexandersson et al.[(27)] the range of daily exposures was 2–85 $\mu$g total NCO/m$^3$ with about 80% of the car painters' exposures exceeding the current 8-hr TWA occupational exposure limit of 20 $\mu$g/m$^3$ of total NCO (Total Reactive Isocyanate Group, TRIG) used by Sweden and the United Kingdom Health and Safety Executive.[(29)]

In the Tornling et al. study[(28)] no range was reported, but a figure suggests that about 55% of the TWA exposures were below the current OEL of 20 $\mu$g/m$^3$ total NCO. In this study, 57% of the painters' ambient TWA exposures were below the current OEL, and none of the office workers or technicians exceeded the 20 $\mu$g/m$^3$ total NCO OEL. Once respirator use was included, none of the subjects had exposures over the U.K. OEL.

Although inhalation has been the major route of exposure considered in most isocyanate exposure assessments, there is mounting evidence that dermal exposure may also play a significant part in isocyanate sensitization.[30–33] A dermal exposure assessment component was added to the study design, and work is currently under way to develop a dermal exposure metric to add to the inhalation exposure metric in future exposure response analyses.

## CONCLUSIONS

The quantitative exposure estimation algorithm was a better exposure index than exposure surrogates such as job title, spray event counts, or iso event counts (spray and near spray events) based on the exposure-response model fit as well as strength and magnitude of the association in a model of cross week change in $FEV_1$. The task-based exposure assessment modeling method used proved useful in addressing the highly variable work patterns of autobody shop workers. In this study, 43% of the painters' ambient TWA exposures were above the current U.K. Health and Safety Executive OEL for total NCO of 20 $\mu$g/m$^3$; however, once respirator use was accounted for, all exposures were below the OEL. Future work to develop a dermal exposure metric is under way.

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